Design of an Explosion Vessel for Study of Flame Propagations

by

Hamizah A Rahman

An dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

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CERTIFICATION OF APPROVAL

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Approved by,

(Dr Ir Shaharin Anwar Sulaiman)

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained here in have not been undertaken or done by unspecified sources or persons.

Hamizah A Rahman

ABSTRACT

This report explains about the design of an explosion vessel in Universiti Teknologi PETRONAS (UTP). Recently, there are many researches and studies about combustion that have been established in the university. In this learning process, an explosion vessel would be a proper medium to study about the flame characteristics and the things that related to the combustion. Hence, a design of an explosion vessel will bring many benefits in UTP. The objective of this project is to design an explosion vessel that will be able to withstand the certain conditions such as maximum working temperature and pressure. The design of the prototype must be durable, reliable and in compliance with the safety regulations and standards to ensure the safe working conditions. The scope of study of this project includes on the design of an explosion vessel starting from the design, material selections, codes of standard and factor of safety. There are several steps in the methodology to design the vessel where the maximum working temperature and pressure are identified in order to calculate the vessel stresses. Suitable materials to build this prototype will be determined based on the vessel stress. The auxiliary items that will be used with the explosion vessel also been studied in order to provide the suitable and safe equipment in the experimental setup of the explosion vessel. As the project completes, technical drawings of the explosion vessel are produced. The specifications of the auxiliary items are also identified in order to ensure that the system working according to experiment requirements. In evaluating whether it is necessary to do impact testing, it is found that the test is not required based on the Minimum Metal Design Temperature (MDMT) procedure.

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NOMENCLATURE

Notation below applies for the reinforcement analysis according to ASME VIII.

A	m^2	Area
$C.A$	mm	Corrosion Allowance
E		Joint coefficient
f		Correction factor which compensate for the variation in vessel stress on different plane of vessel wall
K		Temperature
KPa	N/m^2	Pressure
P	N/m^2	Pressure of design requirement
R	Mm	Radius
S	N/m^2	Tensile strength
S_n	N/m^2	Allowable stress in nozzle
S_p	N/m^2	Allowable stress in the reinforcing plate
S_v	N/m^2	Allowable stress in reinforcing plate
t	mm	Thickness
t	mm	Nominal thickness of the vessel wall
t_e	mm	Thickness or height of reinforcement
t_n	mm	Nominal thickness of nozzle wall
t_r	mm	Required thickness based on calculation

Others

E	mJ, J	Ignition energy
ϕ		Equivalence ratio
m	kg	Mass
n	moles	Number of moles
r	mm	Radius
u'	m/s	Root mean square turbulent velocity

CHAPTER 1
INTRODUCTION

1.1 Background of Study

Combustion studies have been developed worldwide for more than a century. Researchers continuously seek ways to improve optimization of combustion performance and to increase fuel efficiency. In this learning process, methods to examine the explosions are through experiments and observation in closed vessel and to mathematically correlate the flame travel velocity, pressure and time with parameters defining the reaction, either using natural gas or hydrocarbon fuel like iso-octane.

An explosion vessel is an experiment facility with which the combustion studies are conducted. It would be a proper medium to investigate the burning properties of various fuels at wide range of conditions, such as pressure, temperature and turbulence of mixture burning. Such a facility would help to understand the fundamental of flame propagations, flame speed, burning rate of fuels and physical properties involved. Clearly, the design of the explosion vessel would be a milestone to a wide range of combustion researches related to increasing the combustion performance and fuel efficiency.

In this Final Year Project, a study to design of the explosion vessel is done in order to provide a safe and reliable vessel. The vessel is a spherical vessel which has two observing windows, flanges and saddle supports.

1.2 Problem Statement

To understand the combustion studies and extend the learning process related to the characteristics of flame propagations, ignition, flame speed and burning velocity, a design of a constant volume explosion vessel with an optical glass to study the characteristics of flame propagation is required. The explosion vessel must be reliable and safe in the operating condition to avoid any superfluous accident from happening while conducting the experiment.

1.3 Objective

The objective of the project is to design a constant volume explosion vessel for fundamental study of flames and combustion. The vessel must be durable, reliable, and in compliance with the standard safety requirement and regulations in order to ensure safe operating condition.

1.4 Significant of Study

This project is significant since there is no proper device or experiment facility for combustion purpose has been developed in University Teknologi Petronas yet. This design will be a milestone for the development of a prototype of an explosion vessel.

1.4 Scope of Study

This project will cover the process on how to design an explosion vessel starting from the design requirement, material selection, codes of standards, factor of safety and suggestion for fabrication. The main points of scope of study consist of the following:

i) **Combustion Theory-** To start of the project, first things that to be fully understood is the basic theory of the combustion theory. This will help to determine the process that occurs during the explosion and the consequences that might occur correspond to the explosion. In order to simplify the learning process of combustion theory, GasEQ software is used.

ii) **Stress analysis** – Stress analysis is the determination of the relationship between internal to vessel and the corresponding stresses occurs within the explosion vessel

iii) **Material Design** – Proper material need to be selected in order to ensure that the explosion vessel will operate in a safe condition. These processes consist of several subsections, including the selection of suitable material that complies with safety regulations, corrosion allowance and the reliability of the material.

iv) **Codes of standards** – To build up a vessel, there are certain standards that we need to take account in order that the vessel is really reliable and operate in safe condition. There are various standards that we can comply with due to type and usage of the vessel. These codes are intended to provide reasonable protection of life and property and also provide for margin deterioration in service.

v) **Technical drawings** – To produce the prototype of explosion vessel, proper technical drawings are needed. The drawings consist of the main parts of the explosion vessel, and also the attached auxiliary items. The technical drawings are produced at the end of this project as the design of the explosion vessel.

vi) **Factor of safety**– The safety factors are generally applied to the pressure vessel materials so that significance assurances exist and the components can safely perform in operating environment.

vii) **Auxiliary Items** – In order for the explosion vessel to operate, the experimental setup need more than the vessel. These items need to be clarified the functions in order to select the most suitable and incompliance with the safety standards. Among the supporting auxiliary items are like thermocouples for measurements of temperature, pressure transducer for measurements of pressure, heaters to pre heat the explosion vessel to the required operating temperature and fans to provide the homogeneous temperature distribution and turbulence flow in the explosion vessel.

CHAPTER 2

THEORY

2.1 Combustion

The purpose of the design of explosion vessel is to investigate the burning properties at various fuels at wide range of condition, such as pressure, temperature and turbulence of mixture burning. Since the design requirement is based on the iso-octane fuel, the combustion process of this type is fuel need to be well understood. The arrangement of iso-octane hydrocarbon is shown as in Figure 2.1.

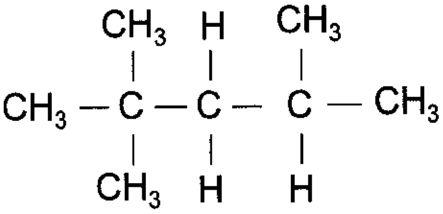


Figure 2.1: The Composition of Carbon and Hydrogen in Iso-Octane.

The complete reaction of a general hydrocarbon C_aH_b with air is:

$$C_\alpha H_\beta + a(O_2 + 3.76N_2) \rightarrow bCO_2 + cH_2O + dN_2 \tag{2.1}$$

where:

C balance: $a = b$

H balance: $b = 2c$

O balance: $2a = 2b + c$

$a = a + b/4$

N balance: $2(3.76)\,a = 2d$

$d = 3.76(a + b/4)$

The stoichiometry proportions of fuel and air is given as:

$$C_\alpha H_\beta + \left(\alpha + \frac{\beta}{4}\right)(O_2 + 3.76N_2) \rightarrow \alpha CO_2 + \frac{\beta}{2}H_2O + 3.76\left(\alpha + \frac{\beta}{4}\right)N_2 \tag{2.2}$$

Hence, for iso-octane, Equations (2.2) results in:

$$C_8H_{18} + (12.5)(O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + 47N_2 \tag{2.3}$$

The stoichiometric mass based air/fuel ratio (A/F) for C_aH_b fuel is:

$$(A/F)_s = \frac{m_{air}}{m_{fuel}} = \frac{\left(\sum n_i \overline{M}_i\right)_{air}}{\left(\sum n_i \overline{M}_i\right)_{fuel}} = \frac{\left(\alpha + \frac{\beta}{4}\right)\overline{M}_{O_2} + 3.76\left(\alpha + \frac{\beta}{4}\right)\overline{M}_{N_2}}{\alpha \overline{M}_C + \beta \overline{M}_H} \tag{2.4}$$

where m_{air} *is* mass of air, m_{fuel} is mass of fuel, $\left(\sum n_i \overline{M}_i\right)_{air}$ is the total of molar mass of air , $\left(\sum n_i \overline{M}_i\right)_{fuel}$ is the total of molar mass of fuel, $\overline{M}_{O_2}$ is molar mass of O_2, $\overline{M}_{N_2}$ is the molar mass of nitrogen, $\overline{M}_C$ is the molar mass of carbon and $\overline{M}_H$ is the molar mass of hydrogen.

Substituting the respective molecular weights and dividing top and bottom with *a* one gets the following expression that only depends on the ratio of the number of hydrogen atoms to hydrogen atoms *(b/a)* in the fuel as presented in Equations (2.5):

$$(A/F)_s = \frac{1}{(F/A)_s} = \frac{\left(1 + \frac{(\beta/\alpha)}{4}\right)(32 + 3.76 \cdot 28)}{12 + (\beta/\alpha) \cdot 1} \tag{2.5}$$

The result yield for the iso-octane (C_8H_{18}), *b/a* = 2.25 where *(A/F)$_s$* = 15.1

For a non-stoichiometric mixture, the reactants on the left side of the Equations (2.1) can be expressed as:

$$\phi C_8H_{18} + 59.5Air \tag{2.6}$$

where ϕ is the equivalence ratio.

Changing it to one mole of mixture,

$$1 \text{ mole reactants} = \frac{\phi}{59.5+\phi}C_8H_{18} + \frac{59.5}{59.5+\phi}Air \tag{2.7}$$

From Equations (2.7), the mole fractions of air and fuel are

$$\frac{n_a}{n} = \frac{59.5}{59.5+\phi} \tag{2.8}$$

while

$$\frac{n_a}{n_f} = \frac{\phi}{59.5+\phi} \tag{2.9}$$

where n_a, n_f and n are the numbers of moles of air, fuel and total mixture. The ratio of the partial pressures of two gaseous species is equal to the mole fractions,

$$\frac{n_a}{n_f} = \frac{P_a}{P_f} \tag{2.10}$$

Where P_f and P_a are the fuel and the total mixture. Following the Equations (2.8) and (2.9), the partial pressure of the fuel can be expressed as

$$P_f = P\frac{\phi}{59.5+\phi} \tag{2.11}$$

2.2 Minimum Ignition Energy and Flammability Limits

According to Turn (2000), a flame is spark-ignited in a flammable mixture only if the spark energy is larger than some critical value known as the minimum ignition energy E_{ign} It is found experimentally that the ignition energy, E_{ign} is inversely proportional to the square of the mixture pressure, P.

$$E_{ign} \propto 1/P^2 \tag{2.12}$$

A flame will only propagate in a fuel-air mixture within a composition range known as the flammability limits. The fuel-lean limit is known as the lower flammability limit and the fuel-rich limit is known as the upper flammability limit. According to Sulaiman (2007), the flammability limit is affected by both the mixture initial pressure and temperature.

2.3 GasEQ

GasEQ was developed as a freeware research tool (Morley, 2006). This software is used to perform combustion equilibrium calculations where it is intended primarily for gas phase calculations. Using GasEQ, a number of different types of calculations can be performed. These include determining compositions at a given temperature and pressure, calculating equilibrium constants such as stoichiometry coefficients and even performing shock calculations like post shock temperature, pressure, and composition.

However, this GasEQ has several limitations which affect the accuracy of the outputs generated under certain circumstances. For an example, GasEQ identifies species from their names, which are assumed to be unique. If the user is attempting to work with several species with the same name, GasEQ will always select the first in the list. This behavior can lead to erroneous results that may go unnoted. The program also does not do a very good job of handing reactions where liquid water is involved (Morley, 2006).

By specifying the initial conditions and the desired output of a fuel-air mixture of a reaction, GasEQ will estimate the resulting products. Typical outputs include temperatures, compositions, reverse reaction rates, equilibrium reactions, and ideal gas law solutions based on thermodynamic data.

According to Morley (2006), GasEQ uses the basic equation of shock and detonation of a two dimensional secant method:

$$P_1 - P_2 + \rho_1 u_1^2 - \rho_2 u_2^2 = 0 \qquad (2.13)$$

$$h_1 - h_2 + 0.5(u_1^2 - u_2^2) = 0 \qquad (2.14)$$

where h's are enthalpies, ρ's are densities and u's are gas velocities relative to the shock. Subscripts 1 and 2 are before and after the shock respectively. The u's are gas velocities relative to the shock and obtained in different ways for incident, reflected and detonation calculations.

For incident shocks the shock speed relative to the stationary gas ahead of the shock is u_1, and the continuity rule gives

$$u_2 = u_1 \rho_1 / \rho_2 \qquad (2.15)$$

For reflected shocks, an incident shock calculation is done first and the gas velocity in lab coordinates after the incident shock, v_S used

$$u_2 = \frac{\rho_1 v_S}{\rho_2 - \rho_1} \qquad (2.16)$$

where u_2 is the sound speed in the burnt gas, and u_1 is calculated from Equation (2.16).

$$u_1 = u_2 + v_S \tag{2.17}$$

For incident shocks with frozen chemistry, the initial estimates are:

$$\frac{T_2}{T_1} = \frac{P_2}{P_1}\frac{2M_1^{-2} + \gamma_1 + 1}{\gamma_1 + 1} \tag{2.18}$$

where γ_1 is the specific heat and $M_{1,}$, in these formulae, is the Mach number. For non-frozen chemistry a combustion calculation is carried out to estimated P_2 and T_2 and

$$h_2 = h_1 + 0.5u_1^2 \tag{2.19}$$

For reflected shocks, the initial estimates are:

$$T_2 = 2T_1 \tag{2.20}$$

2.4 Design Concept of Vessel Shape

For the design of the explosion vessel, some references were made from Fryer and Harvey (2000), in which selection of sphere design for the pressure vessel has been found to be ideal based on 3 reasons:

1. Stress-wise, where it gives the lowest possible value of stress.
2. Storage-wise, where it contains the largest volume with minimum surface area.
3. Cost-wise, where it has minimum thickness and surface area, hence lowest material weight and cost.

But there are also disadvantages in building spherical vessel, in which the manufacturing processes are more difficult and more costly than other vessels.

2.5 Safety Standards

In the design process of this explosion vessel, there are several codes have that been used to ensure that the vessel is reliable and safe in the operating condition. Some of the codes are given in American Society Mechanical Engineers (ASME) Section VIII Division 1. This division outlines the basic codes for designing vessel, where ASME stated its objective as to afford reasonably certain protection of life and property and to provide a margin for deterioration in service do as to give long, safe period of usefulness (ASME Boiler and Pressure Vessel Committee, 2004). Throughout this project, the references for codes are made mainly on ASME VIII Division I. The thickness analysis for vessel under internal pressure is discussed in detail under Subsection A, under UG-27 in Section VIII- Rules for Construction of Pressure Vessels Division 1, 2004 edition.

2.6 Design Factor for Safety

According to Fryer (1998), the factor of safety are the trade off means of establishing equal reliability and safety by assigning to a single parameter varying degrees of quality assurance (design analysis, material testing, fabrication control and in-service control). The ASME has several codes based on different section, according to theory of failure and material property. The design factor is tabulated and shown in Appendix 1.

2.7 Thickness of the Spherical Vessel

The specification for the spherical vessel is outlined in UG-27 in ASME VIII Division 1. With the assumption the design is uniform thickness in the hemispherical condition; the thickness and the maximum allowable working pressure are calculated as the equations tabulated in Table 2.1.

Table 2.1: The equations of ASME Guidelines to determine the wall thickness. Reproduced from ASME Section VIII, Section 1 (2004)

EQUATIONS	REMARKS	CODE REFERENCES	EQUATION NUMBER
$t = \frac{PR}{2SE - 0.2P}$	Equation is used when t is less than 0.365R or P is less than 0.665SE	Par. UG-27(d)	(2.21)
$P = \frac{2SEt}{R + 0.2t}$	P exceeds 0.356R or P exceeds 0.665SE	Par. UG-27(d)	(2.22)

2.8 Corrosion Allowance

From the thickness calculation done, the value obtained is quite small. The value is then added with the Corrosion Allowance (CA). According to the ASME Section VIII Division 1, the normal corrosion allowance that is usually applied on pressure vessels is 0.125 inch or 3 mm.

2.9 Welding Considerations

In order to assemble the vessel components, appropriate welding is needed. Thus, incompliance to Simple Pressure Vessel (Safety) Regulations 1991, Part 3, the preparation of the components parts for example forming and chamfering, must not give rise to the surface defects, cracks or changes in the mechanical properties of those parts likely to be detrimental to the safety of the vessel. According to Guide of Specification for Welding Electrodes and Rods, under Section A6.1, Welding Consideration for Electrodes, the casting skin should be removed from the weld area by machining, grinding, chipping or other suitable means. When repairing casting defects, care should be exercised to ensure removal of any defective metal to sound base metal before welding. Also, all oil, grease, dirt or other foreign material should be eliminated by the use of suitable solvents. If oil, grease or solvents have impregnated the casting, heat should be applied to the area to be welded until the volatilization is no longer observed. A temperature of 400°C generally is sufficient for this operation. If the casting is too greasy, flash heating the welding surfaces to about 540°C should drive off the grease in a gaseous state.

CHAPTER 3
LITERATURE REVIEW

3.1 Design of Body of Explosion Vessel

According to Cameron and Bowen (2000) a spherical geometry of explosion vessel in fully confined-vessel is more desired as compared to that of the cylindrical geometry. However, most of the experiments were conducted in the cylindrical geometry due to the relative simplicity of the mechanical expansion process. The experiments conducted by Cathey (2008) used a cylindrical chamber made out of stainless steel with the internal diameter of 10.16 cm and length of 20.32 cm. The chamber has two optical accesses where the laser entrance is 10.16 cm in diameter and 2.54 cm thick of fused silica, while the laser entrance and exit windows are 2.54 cm diameter.

In the experiments conducted by Rahim *et al.* (2000) both spherical and cylindrical chambers were used as explosion vessels. The spherical chamber consisted of two hemispheric heads made from SAE 4140 alloy steel that were bolted together to make a 15.24 cm inner diameter sphere. The cylindrical chamber was designed to be as nearly identical as possible to spherical chamber, with aspect ratio of one. The inner diameter of the cylindrical chamber was 13.33 cm.

The explosion vessel used by Weiβ (2008) was a massive stainless steel cuboid to withstand the high pressure and temperature with a volume of 2.28 liters, while the optical access into the vessel was achieved by 4 optical windows of 100 mm diameter. The maximum diameter of sphere that would fit into the explosion vessel was 118 mm.

3.2 Material of Body of Explosion Vessel

Most of the explosion vessels for researches were made of stainless steel; among others in the work of Cameron and Bowen (2000), Cathey (2008) and Weiβ (2008). The selection of stainless steel was mainly due to the ability of the material to withstand the heat and corrosion. Based on information gathered (Atlas Steel Products Co., 2004) Grade 316H has higher strength at elevated temperatures and is sometimes used for structural and pressure-containing applications at temperatures above 500°C. This material also has excellent weldability characteristics by all standard fusion methods, both with and without filler metals. The material is also rated as highly machineable. Budinski (2005) stated that in job shop types of machining operations, stainless steel has absolutely no problem in machining if handled properly. Slow speeds, sharp tools and positive feeds are the key to machine the material successfully. Based on the work of Cameron and Bowen (2000), the explosion vessel that they have been using was manufactured from 316 stainless steel drilled hollow bar, where the result was a cylindrical explosion vessel.

3.3 Design of Optical Accesses

The optical accesses are required in the explosion vessel to monitor the process during the explosion occurs and enable to capture the images of the flame propagations. Common material for the design of optical accesses is fused silica due to the excellent mechanical properties such as high of tensile strength and good surface quality. Optical access that does not significantly degrade the transmission of light are required to monitor the process during the explosion occurs and capture the image of the flames. For an example, according to (Cameron and Bowen, 2000) the Phase Doppler Anemometry (PDA) method requires two windows, one for laser beam and another was for the receiving optics. The receiving optics collected scattered light at an angle of between 65-72 degrees from the transmission probe axis. Therefore, the location of the windows is very important if PDA is used as the diagnostic tool. Same situation goes with PIV (Particle Image Velocimetry) and LIF (Laser Induced Fluorescence) systems. PIV relies upon a CCD (Charge Couple Device) digital camera being placed orthogonal to analyse droplets illuminated by the light sheet. Laser Induced Fluorescence also utilizes similar equipment configuration requiring laser sheet access as well as orthogonal camera access. Two windows are again necessary here as an access for the light sheet and CCD camera (Cameron and Bowen, 2000).

The mechanical properties of fused quartz are quite better as compared to other glasses. The material is extremely strong in compression, with a design compressive strength of 1.09×10^9 Pa. The design tensile strength for fused quartz with good surface quality is in excess of 48 MPa, although in practice this value is greatly reduced for safety considerations. Using the factor of safety of seven, (S_{MAX} = 7.0 MPa) and a maximum pressure of 1.0 MPa, the thickness, t, of the 120 mm diameter circular end window and 40mm× 60mm rectangular side windows were determined:

$$t = \left(\frac{P_{MAX} r^2}{2.28 S_{MAX}} \right)^{1/2} \tag{3.1}$$

where P is the maximum pressure of the spherical chamber, r is the radius of the optical access and S_{MAX} is the factor of safety.

The results are found to be 15 mm and 7.5 mm respectively. For further contingency, these dimensions were increased to 25 mm and 12 mm respectively.

3. 4 Impact Testing

According to Moss (2004) since impact testing is a major expense to the manufacturer of a pressure vessel, the designer should do everything to avoid it. Impact testing can always be avoided but may not be the most economical alternative. Following these steps will help eliminate the need for impact testing and, at the same time, will provide the lowest MDMT (Minimum Design Metal Temperature). This MDMT procedure is used to determine the lowest permissible temperature for which Charpy impact testing is or is not required. Following these steps will help eliminate the need for impact testing and, at the same time, will provide the lowest MDMT:

1. Upgrade the material to a higher group.
2. Increase the thickness of the component to reduce the stress in the part.
3. Decrease the pressure at MDMT. This is a process change and may or may not be possible.

3.5 Design of Flanges

For the present explosion vessel, bolted connections shall be used because it will permit easy disassembly of components, such as to clean up the fused silica if the dust covered the observation windows. According to Stainless steel ANSI Pipe Flanges Guide by Alco Datasheet, the bolted connection may vary of different type of flanges according to the applications. Various types of flanges are used based on the jointing method. The flanges and type of gaskets and material built are determined correspond to the service condition, pressure, temperature, thermal shock and cyclic operation (Farr and Jawad, 2001).

In the design of the vessel, bolted connections are used to easy the disassemble of the components of the vessel. There are 3 types of bolted connections:

1. Blind flanged: Standard plate flange with a raised face but no inside diameter.
2. Loose type flange : For this type of flanges, hub and flanges are one continuous structure either by manufacturer or by full penetration welding like welding neck flanges and long weld neck flanges
3. Integral type flange: Neither flanges nor pipe has any attachment or is non-integral. The hub, if it is used, is acting independent of the pipe.

To set the bolted connections of the vessel, the gasket requirement, bolt sizing and bolt loading are determined first. The gasket facing and selection of type depends on the service condition, fluid or gas handled, pressure, temperature, thermal shock and fatigue or cyclic stress (Farr and Jawad, 2001).

Special flange that are required to be designed should be the last choice. In general, the special flanges that as designed are done for large or high pressure utility. According to ASME Section VIII Division 1, the designs of flanges are governed by two conditions:

1. Gasket seating force
2. Hydrostatic end force

3.6 Design of Bolts

According to Moss (2003) in general, bolt should always be used in multiples of 4. For larger diameter of flanges, use many smaller bolts on a tight bolt circle to reduce the flanges thickness. Larger bolts require large bolts circle, which greatly increase the flanges. For low-pressure flanges, the minimum gasket width will reduce the force necessary to seat the gasket, while larger numbers of smaller diameter bolts can be used to minimize the bolt circle diameter and thus reduce the moment arm which governs the flange thickness. High-pressure flanges require a large bolt area to counteract the large hydrostatic end force. Large bolts, in turn, increase the bolt circle with a corresponding increase in the moment arm. Thicker flanges and large hubs are necessary to distribute the bolt loads and to seek a balance between the quantity and size of bolts, bolt spacing, and bolt circle diameter (Moss, 2003).

3.7 Design of Fan in the Explosion Vessel

According to Weiβ (2008) based on the explosion vessel that been used, in order to mix the unburned mixture as well as to generate turbulence during the explosion, eight fans are mounted in the unit. The axes of the fan were collinear to the space diagonals of the cube. As a consequence, the fans were located concentrically within the vessel without blocking the optical vessel. Each fan had a diameter of 45 mm and consisted of 6 blades of 6mm depth and blade angles of 22.5°. The axial distance from a fan to the opposite one was 133 mm, respectively. The fans were driven by electrical motors, which were located in drillings in the corner of the cube. The rotation speed of the fans was controlled by a unit outside the vessel.

According to Lawes (1987) the turbulence velocity was found to be a linear function of fan speed given by

$$u' = 0.0016\,\omega \qquad (3.2)$$

where ω is the fan speed in rpm. In the preparation of the gaseous pre-mixture in the explosion vessel, liquid iso-octane was injected into the explosion vessel through a needle valve. The low pressure ensured complete and fast evaporation. The fans were run at 1500 rpm to improve vaporization of the liquid fuel.

3.8 Saddle Support

According to Carucci (1999) in the design of pressure vessel, the saddle supports that are usually used for the spherical storage tanks are legs, which are supported with cross bracing in order to absorb any external loads. Generally, the support designs are considering several factors; internally like weight, temperature and thermal expansion for the material selection. The additional loading that might be considered are the

1. Static reactions from weight of attached items for example motors, machinery, pipings and also
2. Load of attached internal components.
3. Cyclic and dynamic reactions caused by pressure or thermal variations, equipment mounted on vessel, and mechanical loadings
4. Impact reactions as the explosion occur.
5. Temperature gradients within vessel component and differential thermal expansion between vessel components

The pressure exerted by the load of attached items and static reactions of weight would not be a factor to be considered. In the work of Cameron and Bowen (2001) the material that been used to build the cradle or support of the explosion vessel was mild steel.

3.9 Heating Coil

In the explosion vessel, heating coil is used to pre-heat the explosion vessel to the required operating temperature. In the work by Cathey (2008) the design of the explosion chamber did not use any heating coil because the work was focused on radical production prior to ignition.

From the information gathered from Heatrex Incorporated, tubular and finned tubular heaters may be clamped against or set into a surface, immersed into liquids, molten salts or soft metal, used to heat air in ducts or ovens, or cast in aluminum, lead, concrete or cast iron. To prevent any electrocution and leakage from the explosion vessel in the installation of the heating coil, the wiring must be grounded to prevent any electrocution and shock. Silicon seal will be used to prevent any leakage from the explosion vessel.

From the Industrial Furnace Interiors Inc. (2008), the electric heating element specialists, the rod elements are generally made using 0.204 inch to 0 .5 inch diameter of resistant alloy. Grades of alloy available include 80NI-20CR, 70NI-30CR as well as Iron Chrome alloys with temperature capabilities up to 2350° F. Rod heating elements are used in applications where it is desirable to have radiant heat flow to the internal chamber of the furnace, directly on the work. Elements may be hung on pins or anchors from fire brick or ceramic fiber and used above 1200° F. To protect the element against moisture, tubular elements can be furnished with hermetic seals or vulcanized boots at the end of the element. The data for the material, sheath temperature and the recommended applications for heating coil are tabulated in the Table 3.1.

Table 3.1: The material, maximum sheath temperature, watts per square inch and recommended applications for heating coil. Reproduced from Heatrex (2009)

Sheath Material	Maximum Sheath Temperatures	Watts Per Square Inch	Heater Diameter Available (Inch)	Recommended Applications
Copper	350°F	50	0.250, 0.260, 0.315, 0.375, 0.475, 0.490 and 0.625	Water, non corrosive liquids
Copper-Clad Steel	750°F	20	0.250, .260, 0.315, 0.375, 0.430 and 0.440	Oil immersion, cast in, finned
Stainless Steel	1200°F	30	0.250, 0.260, 0.315, 0.375, 0.490 and 0.625	Corrosive liquids, food processing
Incoloy	1500°F	40	0.250, 0.260, 0.315, 0.375, 0.430 and 0.625	Corrosive liquids, air, clamp on

Based on the information gathered from Heatrex (2008) in order to manufacture the heating coil requested by clients, they need to determine dimensions for the heating coil.

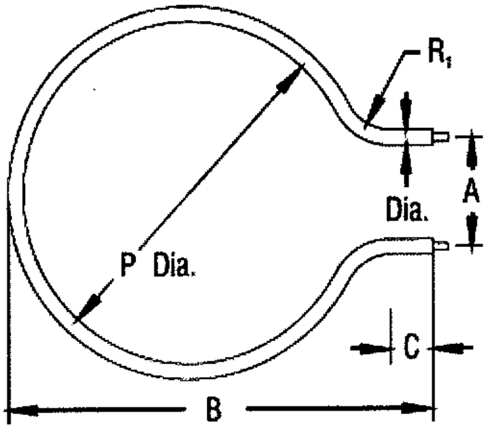


Figure 3.1: The dimension that manufacturer required for heating coil (Heatrex, 2009)

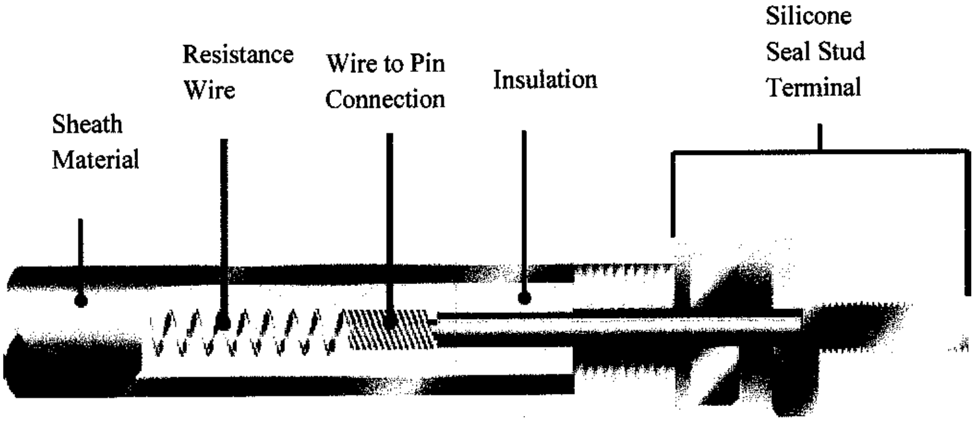


Figure 3.2: The cross section of heating coil (Heatrex , 2009)

3.10 Spark Igniter for Explosion Vessel

According to Weiß (2008) the mixtures of air-fuel were ignited by a high voltage spark plug located in the center of the vessel. The energy of the spark could be modified by changing electrical components in the discharging circuit of the ignition device. For all experiments, the ignition energy was chosen to be as small as possible. The largest ignition energy, necessary to ignite a lean mixture under turbulent flow conditions, was 5.4 mJ.

In the experiment conducted by Cathey (2008) spark ignition was accomplished using a conventional automotive sparkplug and a commercially available automobile ignition circuit, which created a discharge of approximately 40 mJ. For spark ignition tests, the transient plasma electrode was removed and replaced with the sparkplug, which was put in the center of the plate opposite the viewing window.

According to Atzler (1998) in his experiment of burning velocities of droplet suspensions, for the laminar measurements, the ignition energy was approximately 500mJ.

3.11 Thermocouple

Thermocouple is the device that used to measure the temperature. A thermocouple consists of two dissimilar metals, joined together at one end, and produces a small unique voltage at a given temperature. This voltage is measured and interpreted by a thermocouple thermometer. The thermoelectric voltage resulting from the temperature difference from one end of the wire to the other is actually the sum of all the voltage differences along the wire from end to end (The Engineering Toolbox, 2005).

Thermocouple was discovered by Thomas Seebeck's in 1822. He noted that a voltage difference appeared when the wire was heated at one end. Regardless of temperature, if both ends were at the same temperature there was no voltage difference. If the circuit were made with wire of the same material there was no current flow. Thermocouples can be made from a variety of metals and cover a temperature range 200 °C to 2,600 °C

Thermocouples are available in different combinations of metals or calibrations. The four most common calibrations are J, K, T and E. Each calibration has a different temperature range and environment, although the maximum temperature varies with the diameter of the wire used in the thermocouple.

Based on the information gathered from The Engineering Toolbox (2005), there are four classes of thermocouples:

1. The home body class (called base metal)
2. The upper crust class (called rare metal or precious metal)
3. The refractory class (refractory metals)
4. The exotic class (standards and developmental devices)

The home bodies are the Types E, J, K, N and T. The upper crusts are types B, S, and R, platinum all to vary percentages. The exotic class includes several tungsten alloy thermocouples usually designated as Type W.

The explosion vessel used by Cameron and Bowen (2001) are using a k type thermocouple to measure the temperature, because the ability of being used to directly measure temperatures up to 2300 °F. The thermocouple junction is grounded and brought into direct contact with the product of combustion that being measured.

3.12 Needle Valve

In the setting up the experiment, a needle valve is needed to inject the mixture of the fuel into the explosion vessel. According to Atzler (1998) the stoichiometric iso-octane air mixtures were prepared in-situ by injection with a hypodermic syringe through a needle valve. The fuel was injected either using a 5 ml or 10 ml Hamilton Microliter glass syringe. The accuracy of the injected volumes was more than ± 0.015 ml and ± 0.030 ml respectively. The equivalence ratio accuracy found is within ± 0.5 %. After fuel injection, air was added to the initial pressure for the experiment (Sulaiman and Lawes, 2007)

According to Integrated Publishing (2009) needle valves are similar in design and operation to the globe valve. Instead of a disk, a needle valve has a long tapered point at the end of the valve stem. A cross-sectional view of a needle valve is illustrated in Figure 3.3. The long taper of the valve element permits a much smaller seating surface area than that of the globe valve. Needle valves are used to control flow into delicate gauges, which might be damaged by sudden surges of fluid under pressure. Needle valves are also used to control the end of a work cycle, where it is desirable for motion to be brought slowly to a halt, and at other points where precise adjustments of flow are necessary and where a small rate of flow is desired. The usual orifice sizes that available in market are from range of 4 mm up to 10 mm, which can endure pressure up to 34 Mpa (Sealexcel India Pvt Ltd, 2009).

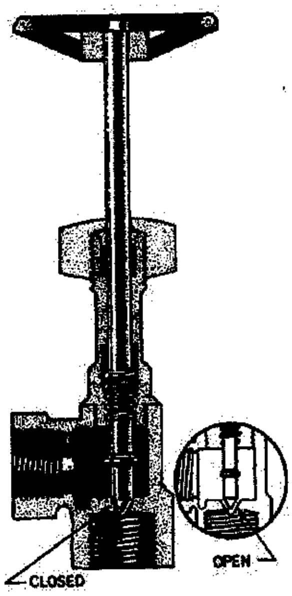


Figure 3.3: The cross sectional view of needle valve (Integrated Publishing, 2009)

CHAPTER 4

METHODOLOGY

4.1 Project Flow Chart

In performing this design project, a simple flowchart is presented as shown in Figure 4.1 to summarize the work and methodology that will be carried during the project duration.

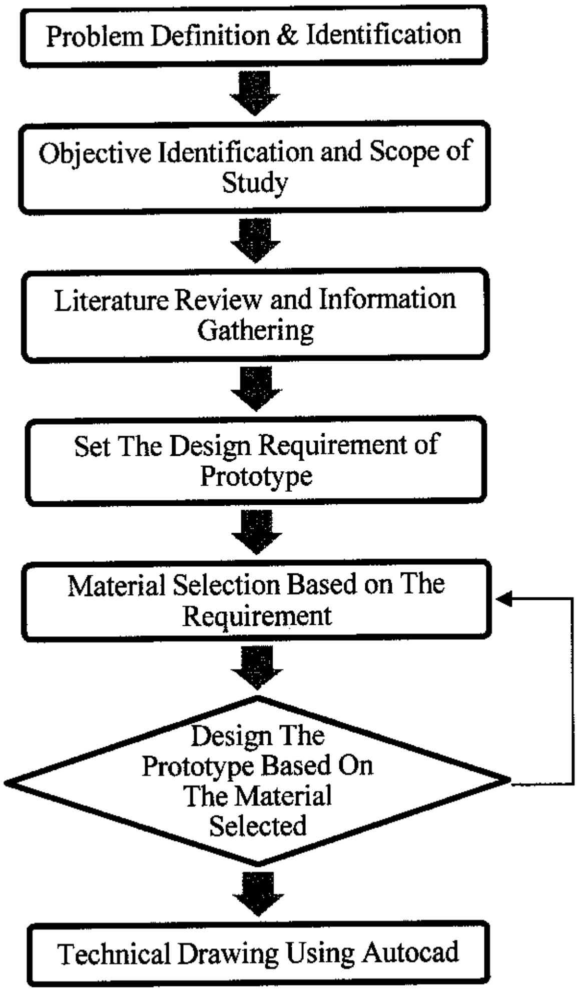


Figure 4.1: The flow chart of methodology for the design of the explosion vessel

In the design process, the first step after the literature review and the gathering information is to plan the design requirement of the prototype. This is obtained by analyzing the combustion theoretically using the GasEQ software. For the initial condition, the problem type selected is Adiabatic Temperature and at Constant Volume. The result of the GasEQ analysis is shown in the chapter of result and discussion. The design requirement of this vessel is mainly based of the maximum pressure and maximum temperature that the materials need to resist to ensure that the vessel is reliable and safe during the operation mode. Based on the temperature and pressure requirement of the explosion vessel obtained, the suitable material for the each component is determined. After the material selection process, the design processes are continued, where the thickness material of the components and the compliance with safety according to ASME Code will be ensured. If the safety regulations did not complied, the material are changed. This process is repeated until proper material found suitable to the explosion vessel. As the final result, the technical drawings are produced in order to fabricate the prototype.

4.2 Tool Required

To accomplish this project, a study on the material characteristics and behaviors are made to find the suitable material for the prototype. Several softwares have been used such as GasEQ, to find the theoretical value of the temperature and pressure while the explosion vessel is in operating condition. Autocad software is used for the technical drawing purpose.

4.3 Gantt Chart

The Gantt chart is prepared in order to ensure that the progress of the project is moving smoothly and within the time. However, the expected result was not obtained due to the inaccurate methodology during the first 8 weeks of the project. Thus, a new methodology was developed as shown in Figure 4.1 and new result was obtained. Although the expected result was not achieved fully, the project was continuously developed to achieve the main objective. The Gantt chart for the design of the explosion vessel for semesters 1 and 2 are shown in the Appendices 2 and 3.

4.4 Design of the Explosion Vessel

Basically, there are two types of vessel that are usually developed for the explosion vessel; i.e. spherical and cylindrical vessel. The selection of the shape of the explosion vessel is determined by comparing the both type of vessel in the Table 4.1

Table 4.1: Comparison between spherical and cylindrical shape of explosion vessel

Type Factor	Spherical	Cylindrical
1. Stress	Lower possible value of stress because the stress distribution is uniform throughout the vessel	Higher possible value of stress.
2. Cost for material	Minimum thickness and surface area, lower weight and cost for material.	Higher thickness and surface area, higher weight and cost.
3. Construction	More complicated, more expensive for fabrication purpose.	Less complicated, less expensive for fabrication purpose.

Theoretically spherical vessel is more reliable than cylindrical. But construction is more complicated than cylindrical. In spherical vessel stress distribution is uniform throughout the vessel. This is safer than cylindrical geometry.

4.5 Design Requirement of the Explosion Vessel

The design requirement of the explosion vessel is determined in order to start the design of the explosion vessel. The design requirement for maximum temperature and pressure is based on the theoretical calculation in GasEQ software, while the size of the vessel and the optical access is determined based on the literature review.

Table 4.2: The design requirement for the explosion vessel based on the GasEQ Software

PARAMETER	VALUE
PRESSURE	938.5 kPa
TEMPERATURE	2641.4 K
SIZE	305 mm (Internal diameter)
OPTICAL ACCESS	2 (150 mm)

4.6 Material Selection of the Explosion Vessel

The material selection of the explosion vessel body is based on several factors. In order to select the most suitable material for the explosion vessel body, a decision matrix is used to rate several material that have the desired criteria for the explosion vessel body such as ability to withstand high temperature and pressure , as well as high corrosion resistance . The materials that have been considered are stainless steel, low carbon steel and aluminium alloy. This three materials are selected based on the literature review, where they are the most common metal that been used in the fabrication of explosion vessel. The justification for each material are referred to Engineering Materials

(Budinski, 2005) and Manufacturing Process for Engineering Materials (Kalpakjian, 2003).

Table 4.3: The decision matrix for material selection of body for explosion vessel

Criterion	Weight	Stainless Steel 316 (Austentic Steel)	Low Carbon Steel (Ferritic Steel)	Aluminium Alloy
Ability to withstand high temperature and pressure	3	5 x 3 =15	3 x 3 =9	3 x 3 =9
Ability to withstand high impact	3	5 x 3 =15	5 x 3 =15	3 x3 =9
Ability to withstand corrosion	3	5 x 3 =15	1 x 3 =3	5 x 3 =15
Machinability Index (Ease to Fabricate)	2	3 x 2 =6	5 x 2 =10	5 x 2 =10
Weldability	2	5 x 2 =10	5 x 2 = 10	5 x 2 = 10
Price	2	3 x 2 =6	5 x 2 = 10	5 x 2 =10
TOTAL		67	57	63

Scoring: 5=high
3=medium
1=low

Based on the decision matrix built, the most suitable material for the explosion vessel is stainless steel, mainly because the characteristic of the material that able to withstand high temperature and pressure, also the ability to withstand the high impact.

4.7 Material Selection for Optical Glasses

In order to determine the material for optical observation glasses, several types of glasses has been compared in the decision matrix. The materials that have been justified to build this decision matrix are Germania Glass, Fused Silica and Borosilicate. Germania Glass usually used for reagent for fiber optic production, while Borosilicate is used for laboratory glassware and reflective optics in astronomy applications. Fused silica often used as the envelope of halogen lamps, in the high temperature applications. Due to its thermal stability, it is used in the semiconductor fabrication furnaces. The justification of each of the material is based in the Handbook of Glass Properties (Bansal, 2006)

Table 4.4: The decision matrix for material selection for optical glasses

Criterion	Weight	Germania Glass (GeO_2)	Fused Silica (SiO_2)	Borosilicate (Pyrex, Duran)
Glass Transition Temperature	3	3 x 3 = 9	5 x 3 =15	3 x 3 =9
Coefficient of Thermal Expansion	3	3 x 3 =9	5 x 3 =15	1 x 3 =3
Density at 20° C, [g/cm^3], x1000 to get [kg/m^3]	2	3 x 2 =6	3 x 2 = 6	3 x 2 =6
Refractive Index n_D at 20°C	2	1 x 2 =2	3 x 2 =6	5 x 2 =10
TOTAL		26	42	28

Scoring: 5=high
3=medium
1=low

Based on the justification made using the decision matrix, the most suitable material for the optical glasses is fused silica, mainly because of the material characteristic of high glass transition temperature and the low coefficient of thermal expansion.

4.8 Thickness Calculation of the Spherical Vessel

The specification for the spherical vessel is outlined in UG-27 in ASME VIII Division 1. With the assumption the design is uniform thickness in the hemispherical condition;

the thickness and the maximum allowable working pressure are calculated as the equations that have been tabulated in Table 4.5.

Table 4.5: The equations of ASME Guidelines to determine the wall thickness. Reproduced from ASME Section VIII, Section 1 (2004)

EQUATIONS	REMARKS	CODE REFERENCES	EQUATION NUMBER
$t = \frac{PR}{2SE - 0.2P}$	Equation is used when t is less than 0.365R or P is less than 0.665SE	Par. UG-27(d)	(4.1)
$P = \frac{2SEt}{R + 0.2t}$	P exceeds 0.356R or P exceeds 0.665SE	Par. UG-27(d)	(4.2)

where *t* is the thickness of the vessel, *P* is the design pressure of the vessel, *R* is radius of the vessel, *S* is material's tensile strength of the vessel and *E* is the joint efficiency of the vessel.

4.8 Thickness Calculation of Optical Glasses

The calculation for the sight glass thickness, t, is using the same equation used by Cameron and Bowen (2000):

$$t = \left(\frac{(P)(r)^2}{2.28(S_{MAX})} \right)^{1/2} \quad (4.3)$$

where P is the maximum pressure of the spherical chamber, r is the radius of the optical access and S_{MAX} is the factor of safety.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Design Requirements

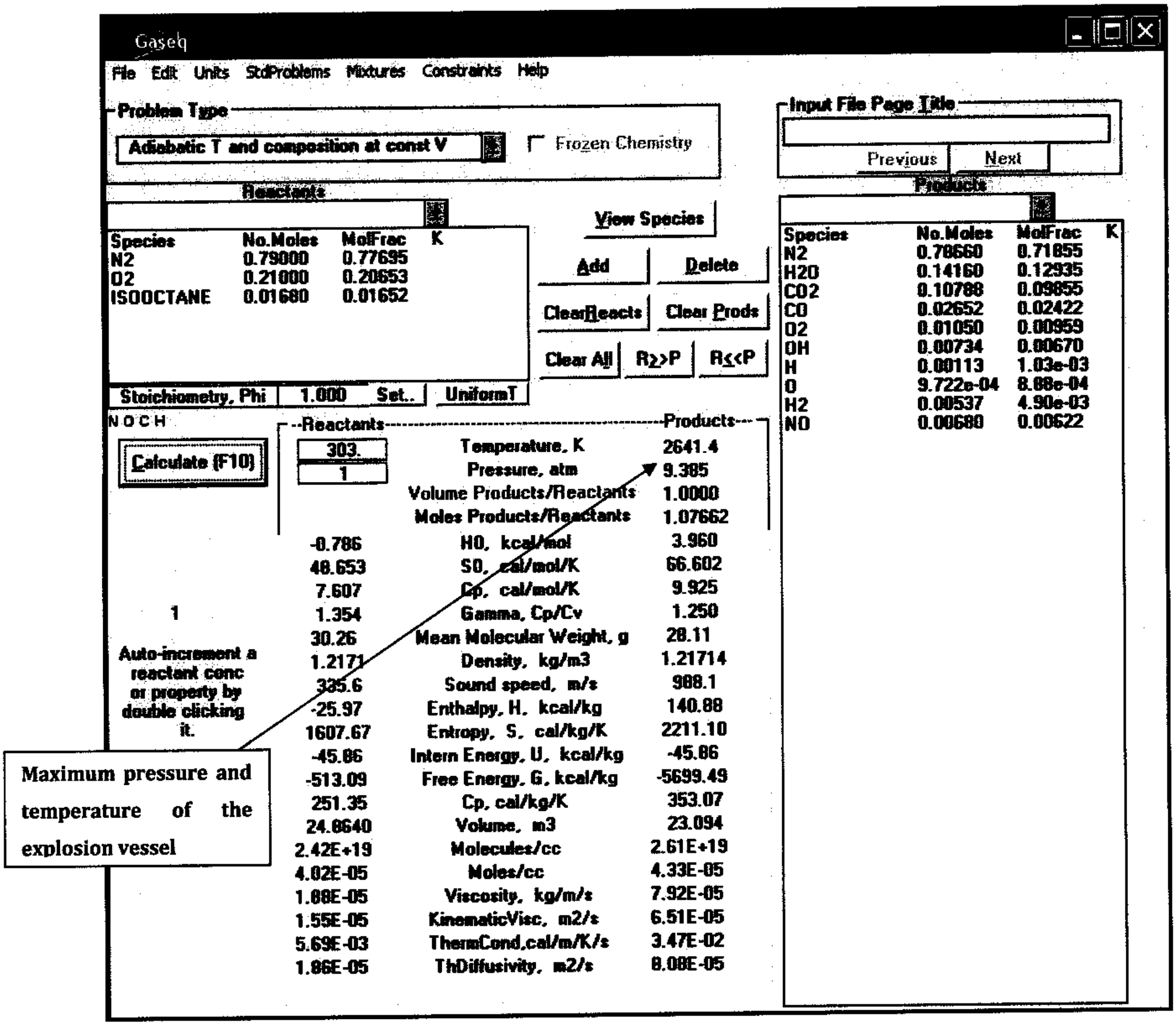
The design requirements of the explosion vessel are obtained by analyzing the combustion theoretically using the GasEQ software. For the initial condition, the problem type selected is Adiabatic Temperature and composition at Constant Volume. The result of the Gaseq analysis is shown in Figure 5.1. The reactants, or the fuel used is iso-octane, about 1.68 %, mixed with the N_2 as the biggest portion (79 %) and O_2 about 21%. Table 5.1 shows the design requirement of the explosion vessel based on the calculation in GasEQ Software.

Table 5.1: The design requirements for the explosion vessel based on the Gaseq Software.

PARAMETER	VALUE
PRESSURE	938.5 kPa
TEMPERATURE	2641.4 K
SIZE	305 mm (Internal diameter)
SIGHT GLASS	2 (150 mm)

5.2 Material Selection and Wall Thickness of the Vessel

Based on the design requirement, calculation to determine the wall thickness of the vessel can be done using the specification of calculation for spherical vessel is outlined in UG-32 in ASME VIII Division 1. Previously, during the early stage of the project, the material selected for the vessel was the cast iron A48 Class 20. However, the material was found not suitable for the design since the tensile strength and the yield strength is same.



Problem Type: Adiabatic T and composition at const V

Reactants

Species	No.Moles	MolFrac	K
N2	0.79000	0.77695	
O2	0.21000	0.20653	
ISOOCTANE	0.01680	0.01652	

Stoichiometry, Phi 1.000

Products

Species	No.Moles	MolFrac	K
N2	0.78660	0.71855	
H2O	0.14160	0.12935	
CO2	0.10788	0.09855	
CO	0.02652	0.02422	
O2	0.01050	0.00959	
OH	0.00734	0.00670	
H	0.00113	1.03e-03	
O	9.722e-04	8.88e-04	
H2	0.00537	4.90e-03	
NO	0.00680	0.00622	

Reactants		Products
303.	Temperature, K	2641.4
1	Pressure, atm	9.385
	Volume Products/Reactants	1.0000
	Moles Products/Reactants	1.07662
-0.786	H0, kcal/mol	3.960
48.653	S0, cal/mol/K	66.602
7.607	Cp, cal/mol/K	9.925
1.354	Gamma, Cp/Cv	1.250
30.26	Mean Molecular Weight, g	28.11
1.2171	Density, kg/m3	1.21714
335.6	Sound speed, m/s	988.1
-25.97	Enthalpy, H, kcal/kg	140.88
1607.67	Entropy, S, cal/kg/K	2211.10
-45.86	Intern Energy, U, kcal/kg	-45.86
-513.09	Free Energy, G, kcal/kg	-5699.49
251.35	Cp, cal/kg/K	353.07
24.8640	Volume, m3	23.094
2.42E+19	Molecules/cc	2.61E+19
4.02E-05	Moles/cc	4.33E-05
1.88E-05	Viscosity, kg/m/s	7.92E-05
1.55E-05	KinematicVisc, m2/s	6.51E-05
5.69E-03	ThermCond,cal/m/K/s	3.47E-02
1.86E-05	ThDiffusivity, m2/s	8.08E-05

1

Maximum pressure and temperature of the explosion vessel

Figure 5.1: The result of explosion based on GasEQ calculation for stoichiometry mixture at P = 1 atm, T = 303 K and Ø = 1

This indicates that the material might not be able to withstand the impact load produced by the explosion in the vessel. Hence, an alternative material is used. According to most of related literature review, explosion vessels were mainly produced using the stainless steel. The reason of why this material was chosen was due to the ability to withstand the heat and corrosion. Furthermore, the material is available worldwide and easy to fabricate.

Steel 316 is the most suitable material in this design according to Atlas Steel Australia since it has properties that good oxidation resistance in intermittent service to 870°C and in continuous service to 925°C. Grade 316L is more resistant to carbide precipitation and can be used in the above temperature range. Grade 316H has higher strength at elevated temperatures and is sometimes used for structural and pressure-containing applications at temperatures above about 500°C.

According to Kalpakjian (2000), stainless steel is characterized primarily by their corrosion resistance, high strength and ductility and also high chromium content. They are called stainless because, in the present of oxygen (air), they develop a thin, hard adherent film of chromium oxide that protects metal from oxidation. These protective films built up again if the surface is scratched. To fabricate this type of spherical vessel, casting process would be consider as the most suitable process, since the castability of the steel rated as fair to good, while the weldability is rated excellent, and the machinability is rated to fair to good. However, the casting of stainless steel will present some difficulties since generally, the freezing range is long and has high melting temperature. Cast stainless steels are available in various compositions, where they can be heat treated and welded. These cast products have high resistance to heat and corrosion. The tolerance of the casting products should be as wide as possible, where in commercial practice, tolerances usually are about $\pm 0.8mm$, for small castings and increase with size of casting, about $\pm 6mm$ for large castings.

Stainless steel is also less brittle compared to the previously proposed cast iron. The thickness of the explosion vessel then was calculated by changing the material to stainless steel 316. The results are shown in Table 5.2.

Table 5.2: The thickness of the vessel wall.

Material	Tensile Strength (MPa)	Yield Strength (MPa)	Thickness of the wall (mm)
Stainless Steel 316	515	205	25

By calculation that performed using the equation in the ASME guidelines, the vessel wall thickness is 3.15 mm. However, according to the literature review done, most of explosion vessels produce are around 20 mm. This is to ensure that the vessels have enough strength to withstand the maximum pressure and temperature. For the design, the vessel thickness has been increased to 25 mm.

To determine the thickness of the nozzle for the optical glasses and the nozzle for input and output, calculations are done as attached in Appendix. The thicknesses of the nozzles also need to be increased in order to make them strength and fit to proper welding to the main body of spherical vessel. The detail calculation of the vessel wall thickness and nozzle thickness are attached in Appendix 4.

5.3 Material Selection and Thickness Calculation of the Optical Glasses

There are two optical accesses at the spherical vessel, where each diameter of the glass is 150 mm. This is because the observation of the flame is usually starting from the smaller diameter and it will propagate and grew bigger until it stops. The location of the glass is situated in the middle of the outer sphere vessel because the propagation of the flame is most suitable to be view from this point. Fused silica was chosen since it can withstand the high pressure and temperature. Besides, it is a good UV transparency material and can be lapped and polished to fine finishes. The calculation for the sight glass thickness, t, is using the same equation used by Cameron and Bowen (2000):

$$t = \left(\frac{(3285)(0..085)^2}{2.28(7000)} \right)^{1/2} \tag{5.1}$$

The result yield is 20.6 mm. According to the previous literature review, the ranges of thickness of the observation windows are around 24 mm to 25 mm, although the calculation of thickness only required about 15 mm. For further contingency, the thickness of the glass has been increased to 30 mm.

5.4 Design of Opening for Optical Accesses

In order to put the observations window on the spherical vessel, openings are needed for the fused silica glasses to be mounted in. The spherical vessel has to allow two openings for two observation windows. What makes this task difficult is the strength of vessel has to be sacrificed as the hole of opening built on the body. The reinforcement element might need to be added in order to support the strength of the vessel. The thicknesses of the openings are calculated based on the material selected, stainless steel 316. To determine the area required to compensate the opening area in order to cater the stress developed at the vessel wall, calculations made to determine the areas below:

1. Area available in shell, A_1
2. Area available in nozzle, A_2
3. Area available at protruding, A_3
4. Area available in weld, A_4

The summation of above areas will determine whether reinforcement element is needed or not. If the summation is greater than the required area of reinforcement, A, then no reinforcement area is necessary. After considering the strength reduction factor and the protruding length, it was found that there is no need for the addition of reinforcement elements. The detail of calculation can be found in the Appendices 5 and 6.

5.5 Design of Flanges

Flanges are needed to fix the observation windows on the spherical vessel simultaneously to ensure there is no leak when the vessel in operation. The flanges that have been chosen are lap joint flanges with raised face. The lap joint flanges are used in application where the joint where the joint can be frequently disassembled for cleaning, which are most suitable for the explosion vessel observation window since the window might need frequent cleaning due to dust or particles that can block the view. However, according to the Stainless Steel ANSI Flanges Datasheet, the pressure that the flanges could endure might not as high as ring type joint flanges. But, the value of highest pressure that both flanges could hold is same, around 2500 psi. So, it will not be problem in the design.

The material of the flange is stainless steel plate flanges that produced from quality mill plate. Mill plate produced to the ANSI SA240 standards is able to tolerate voids, non-metallic inclusions and other defects. The inherent corrosion resistance of stainless steel is enhanced by the superior grain structure offered by plate products over forged or cast products.The inner diameter of the flanges is 150 mm, and the outer diameter is 308 mm. The bolts holes are about 19.05 mm with tolerances of 1 mm. This is according to the ANSI Datasheet that every hole must be within 5 percent tolerances. As the minimum bolts spacing in the ASME guidelines is 76.2 mm (3 inches), the spaces between bolts at the flanges are about 95 mm (3.73 inches). To avoid or minimize any leakage from the vessel, O-Ring is used as the seal material. According to the standard metric O-Ring size from the Lutz Company, the nominal size for the flanges is 4 mm x 196 mm, where the 4 mm is the width of the O-Ring and the 196 mm is the internal diameter. The seal is designed to have a point contact between the O-ring and sealing faces. This allows a high local stress, able to contain high pressure, without exceeding the yield stress of the O-ring body. The material for O-Ring is fluorocarbon, where the compounds exhibit excellent high temperature resistance and low compression set. Furthermore, it is suitable for dynamic applications and can withstand the high impact repeatedly. The dimensional drawing of the flange is included in the Appendix of Technical Drawing B.

5.6 Design of Bolts

The material selected for the design is ASTM A193, Grade B16, and heat treated chromium-molybdenum-vanadium steel for high-pressure, high-temperature service. According to Moss (2005), from Table 2-5b where is attached in Appendix 9, for the selected type of flanges, lap joint with raised face and the nominal pipe size of 150 mm, or approximately 6 inches, the number of bolting required is 8, with diameter 19.05 mm

(¾ inches) and the length of stud bolts is 95.25 mm (3¾ inches). Referring to Table 2-5a that attached in Appendix 9, the bolt need 10 standard threaded. The minimum bolt spacing is 44.45 mm (1 ¾ inches) and the preferred spacing is 76.2 mm (3 inches). The dimensional drawing is included in the Appendix of Technical Drawing C.

5.7 Design of Fan in the Explosion Vessel

In the design of this spherical vessel, there are 4 fans in the explosion vessel. The fans' function is to provide the homogeneous temperature distribution in the explosion vessel. In the laminar combustion experiment, they are used to mix the fuel and air, according to the experiment requirement, while in turbulent combustion experiment, fan is used to provided the turbulence flow. The material for the fan is stainless steel. The axes of the fan were collinear to the space diagonals of the vessel. This design is to avoid blocking the optical vessels. Each fan had a diameter of 75 mm and consisted of 8 blades of 45 mm depth and blade angles of 22.5°. The shafts are supported by the sleeve wear, where the wear sleeve will provide a protective seal running surface and become the part of the shaft. Bearing must be centralized at the shaft to avoid any excessive vibrations or moving around where the consequence is the shaft will be damaged. The fans were driven by electrical motors, which were located out of the vessel. The proposed motor to be used with is a 3-phase 1.5 kW motor which is controlled by the electronic motor controllers. The dimensional drawing is included in the Appendix of Technical Drawing D.

5.8 Schematic Drawing of the Explosion Vessel Experimental Setup

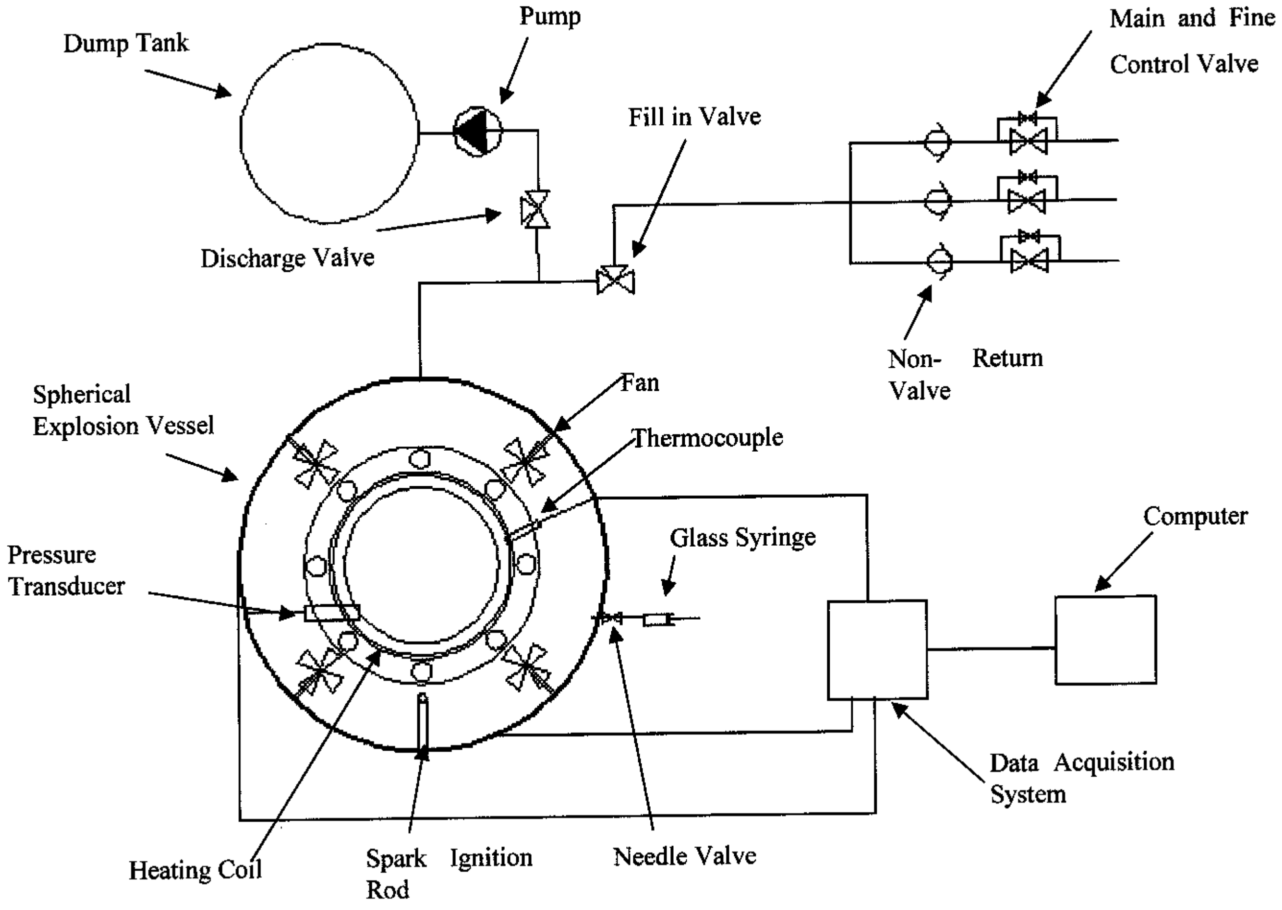


Figure 5.2: The schematic drawing of the explosion vessel experimental setup.

From the sketch, it can be observed that the system of the explosion vessel. In the design, there will be 2 optical glasses on the vessel body. The functions of these optical glasses are to monitor the process during the explosion occurs and capture the image of the flames. The system consist of the explosion vessel and the auxiliary items to be used with the explosion vessel, such as the pressure transducer to measure the pressure during the operation, thermocouple to measure the temperature and heater to raise the vessel temperature according to the initial experiment requirement. There are 4 fans in the explosion vessel. The fans' function is to provide the homogeneous temperature distribution in the explosion vessel. In the laminar combustion experiment, they are used to mix the fuel and air, according to the experiment requirement, while in turbulent combustion experiment; fan is used to provide the turbulence flow. Throughout all the readings and researches the most common way to ignite the explosion is by using the electric spark discharge. In the experiment, liquid iso-octane will be injected into the explosion vessel through a needle valve. The needle valve is connected to a glass syringe, where the capacity of the syringe depends on the volume required of the experiment. The fans that running in the explosion vessel will mix the liquid with the dry air that connected to the vessel. A system is needed to gather all the information gathered during the experiment. The value of initial condition and the result yield from the experiment is saved in a data acquisition system. All the pressure and temperature measured will be recorded in a data logger. After the explosion occurred, the gas that been produced will be pumped by the single vacuum pump, and will be deliver to the dump tank. The specifications of the components of explosion vessels are tabulated in the Table 5.3.

Table 5.3: Specification of explosion vessel's components.

Part of Components	Materials	Size
Sphere Body	Stainless Steel 316	ID = 305 mm OD= 355 mm Thickness = 25 mm
Observing Window	Fused Silica Quartz	ID = 150 mm OD = 170 mm Thickness = 30mm
Nozzle For Observing Window	Stainless Steel 304	ID=150mm OD=198mm Thickness = 24mm Length = 62.5mm
Flanges	Stainless Steel 316	ID= 150 mm OD= 308 mm Raised Face =15mm
Bolts	ASTM A193,Grade B7	No= 8 Diameter= 19.05 mm Length = 95.25 mm
O -Ring	Fluorocarbon	Width = 4.0 mm
Fan	Stainless Steel	No = 4 Diameter = 75 mm Blade = 8 Height = 45 mm Blade Angle = 22.5 mm
Vessel Support	Stainless Steel	Height = 80mm (measured from the middle) Square Foot = 900 mm^2 Base Height =10mm Base Length = 400 mm

Table 5.4: The auxiliary components used with the explosion vessel.

Parts of Components	Material	Specifications
Thermocouple	Type K (ANSI TYPE)	Temperature Range: (-292.73 K to 4052.93K) or (-565.88 C to 3779.78 C)
Pressure Transducer	316L for diaphragm and housing	Pressure Range: 0 to 1000 psig (6984 kPa)
Heating coil	Incoloy	ID = 310 mm OD = 322.7 mm Diameter =6.35 mm

5.9 Thermocouple

Thermocouple is used for the temperature measurement in the system. In this explosion vessel, the proposed thermocouple to be used is the Type K sheathed thermocouple with 1.5 mm diameter wire. This type of thermocouple is selected based on the ability of being used to directly measure temperatures up to 2300°F. Furthermore, the thermocouple junction may be grounded and brought into direct contact with the product of combustion that being measured. The specification of thermocouple selected is shown in Table 5.5.

Table 5.5: Specification of thermocouple Type K will be used in explosion vessel.

Instrument	Temperature Range		Accuracy
	Recommended(K)	Maximum (K)	
Type K probes	273 to 1513	23.15 to 1648.15	0.4% of reading above 273 K

5.10 Heating Coil

The main function of the heating coil is to set the temperature of the explosion vessel to the initial temperature that required in the experiment. The heater will be used in conjunction with the running fans in order to generated homogeneous temperature distribution throughout the explosion vessel. According to manufacturer, Heatrex Company, the most suitable heating coil is made of incoloy and has width of 6.35 mm while the inner diameter of the heating coil is 310 mm. Incoloy is selected for the material because the maximum sheath temperature could endure temperatures of up to 1888 K. It will require 240 Volts for operation where the watt densities recommended is 40 Watts/inch^2. It applied resistance welded terminals assure a strong mechanical and electrical joint. Magnesium oxide powder is used to electrically insulate the resistance wire assembly which is accurately centered into the heater sheath. The material is then compacted to the optimum density when the diameter of the unit is reduced by rolling.

This greatly improves its thermal conductivity and increases its excellent dielectric strength.

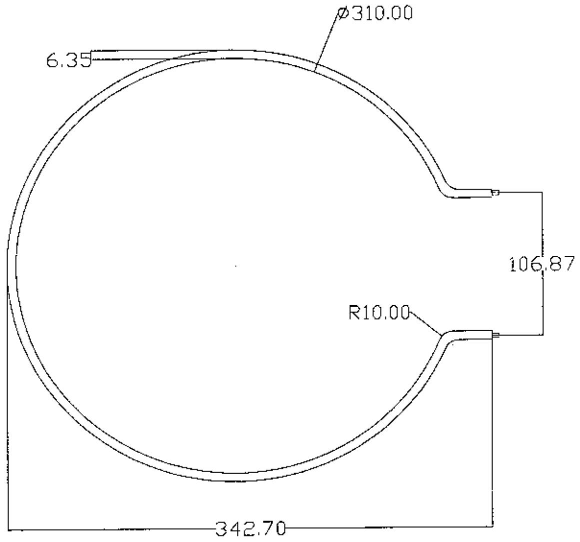


Figure 5.3: The dimensions of heating coil in the explosion vessel in mm unit.

5.11 Pressure Transducer

The most suitable model that suitable to the explosion vessel according to Omega Company is DPX 101-1K, because it can stand the pressure up to 1000 psi or approximately 6984 kPa. The specification of the pressure transducer is as be given by the manufacturer, Omega Company, where the rated output is 5 V and the rise time is 1.0 μs. The resonant frequency of the device is 500 kHz, while the maximum vibration that can withstand is approximately 5000g. The main reason why this type of device is selected is because the ability to withstand the high pressure and the frequency response is higher than 100 Hz. The device is also ideal for monitoring of explosion or pulsation pressures. More information about the pressure transducer is attached in Appendix 14.

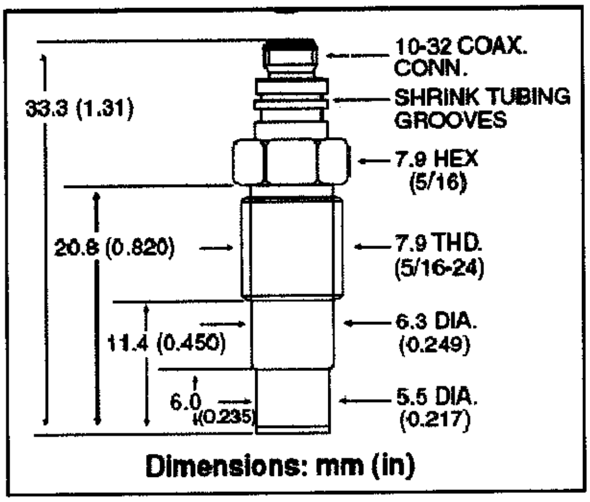


Figure 5.4: The dimension of pressure transducer for explosion vessel (Omega Engineering Inc, 2009).

5.12 Spark Igniter for the Explosion Vessel

The function of the spark igniter is to spark ignite in the explosion vessel. The suitable spark igniter for the explosion vessel is a spark plug that connected to an ignition exciter where the energy of the spark can be controlled. The electronic ignition system controlled by the data acquisition program provides a spark with the desired energy. According to the manufacturer, Chentronics Company, the ignition exciter system, which is Model Number 07070112DIX has output voltage of 5KV,and the spark rate is 4 sparks per second. The stored energy is 12 Joules while the input range is 100 V to 240 V. The electrode rod that used with this ignition system has the outer diameter of 15.8 mm.

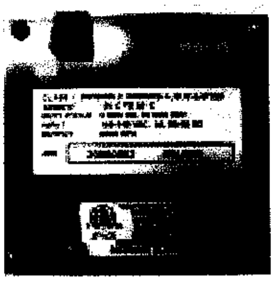


Figure 5.5: Ignition exciter system for the explosion vessel system (Chentronics, 2009).

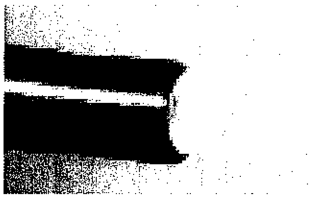


Figure 5.6: The electrode rod of the explosion vessel system (Chentronics, 2009).

5.13 Seal for the Explosion Vessel

Seals are needed to ensure there are no gas or air-fuel leakage from the parts that been installed in the explosion vessel, for example the fan and the auxiliaries items such as pressure transducer, thermocouple and the spark ignition rod. For the seal, the criteria that been important to look at are the abilities to withstand the high temperature of the explosion operation and to withstand the impact of the explosion, otherwise the lifespan of the seal will be short. The seal of the fan parts are the hardest part, since the bearing system of the fan must be designed properly and located at the center of the shaft to avoid the shaft to moving around and damage the seal. A wear sleeve is used with the shaft, where the wear sleeve will provide a protective seal running surface and become the part of the shaft. Since the fan rotates before the explosion, the pressure consideration is according to the initial pressure before the explosion happens.

The shaft run out should be avoided or kept within a minimum. At higher speeds there is a risk that the inertia of the lip seal prevents it from following the shaft movement. The seal must be located next to the bearing and the bearing play be maintained at the minimum value possible. According to Trelleborg Sealing Solution Company, the material that suitable to use with the lip seal is Fluoroelastomer (FKM). This material is an excellent elastomer for use in high temperature applications. The selection of this material based on the graph in Appendix 15.

According to the Gulfcoastseal Company, standard oil seals from automotive industry and pump industry mean 1700 rpm but no more than 40 kPa. For the high pressure equipment, there are high pressure seals for rotation, 210 kPa at 800 rpm. Based on the design made by manufacturer American Seal and Packing Incorporation, for the stationary parts such as thermocouple, pressure transducer and rod for spark ignition, the seal that is most suitable is using the high temperature seal that made from mika. They claimed that this material which has been formed to tape sheet has the capability to withstand the high temperature, up to 2000 K and also high ability to absorb shock impact.

5.14 Needle Valve

Needle valve is needed to insert the mixture of the fuel into the explosion vessel. According to the Swagelok Company, the needle valve that they producing are made from forged 316 stainless steel, where the non rotating needle promotes leak-tight shutoff and long service life. Packing material for the needle valve is PTFE. The needle valves can withstand up to 1450 KPa in the working pressure and temperature up to 800 K. The inlet of the valve is connected to the hypodermic syringe while the outlet needle valve will be connected to the ¼ inches BSP to connect it to the explosion vessel. The dimension of the needle valve is according to Figure 5.7.

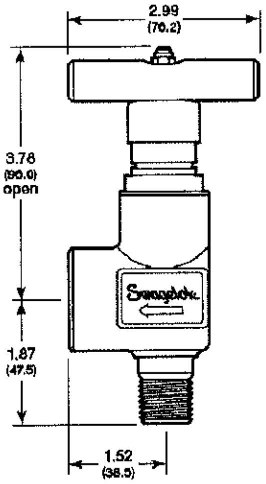


Figure 5.7: The needle valve for the fuel injection in the explosion vessel (Swagelok, 2009).

5.15 Impact Testing

The requirement of impact test for the explosion vessel is determined using the MDMT (Minimum Design Metal Temperature) procedure, which is usually used to determine the lowest permissible temperature for which Charpy impact testing is or is not required. The ASME Code rules for MDMT are built around a set of material exemption curves. The procedure of decision-making process to determine MDMT and impact testing requirements are shown in the flow chart shown in the Appendix. Based on the graph and curves UCS-66(b), the result of the calculation and the graph is as shown.

Ratio of the required thickness based on calculation to the nominal thickness of the wall vessel without corrosion allowance, which as shown in Equation 5.2.

$$Ratio = \frac{t_r E}{t_n - c} \qquad (5.2)$$

$$Ratio = \frac{3.15(1)}{25-3} = 0.14318$$

where t_r is the calculated thickness of the vessel wall multiply with E, the joint efficiency and t_n is the nominal thickness of the wall vessel, where need to minus the corrosion allowance, c.

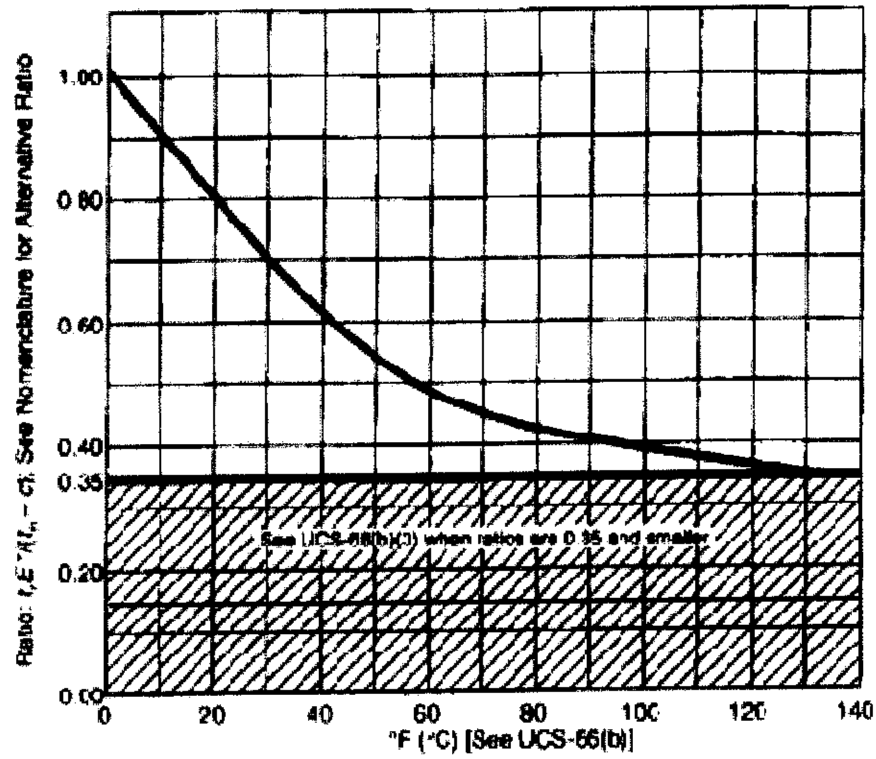


Figure 5.8 Reduction in minimum design metal temperature without impact testing (Moss, 2004)

Since the value of the ratio is less than 0.35, the UCS-66(b) (3) is used. The MDMT for the explosion vessel body is -29 C, while the thickness of the vessel body is 25 mm.

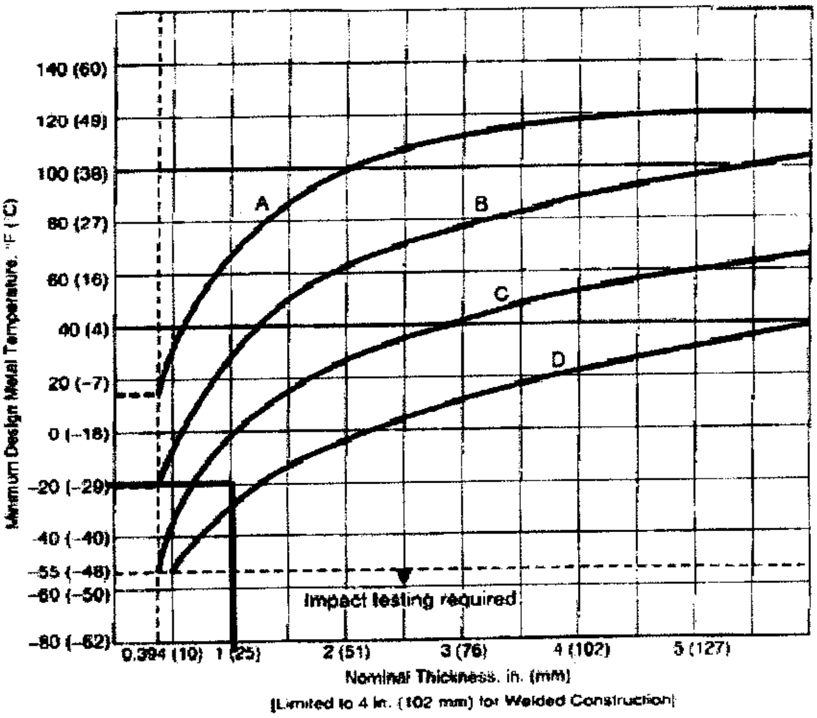


Figure 5.9: Impact test exemption curves (Moss, 2004)

From the graph, it is found that that both of the lines cross up from the line where the impact testing is required. So, the impact testing is not necessary for this vessel.

5.16 Inspection

To ensure that the explosion vessel is properly integrated and has no leakage, inspection should be done to the whole vessel, particularly at the welded area. The suggested inspection to be implemented is the ultrasonic inspection. In this type of inspection, the ultrasonic beam will be travels through each part of the vessel. Any defect, such as crack will interrupt the beam and reflects back a portion of the ultrasonic energy. According to Kalpakjian (2003) the most suitable range of frequency for the vessel inspection is 1 to 25 MHz. Couplants are used to transmit the ultrasonic waves from the transducer to the vessel. The typical couplants that used are oil, glycerin and grease. This method selected because it has high penetrating power and high sensitivity. However, this method requires experienced personnel to carry out the inspection and interpret the result correctly.

5.17 Estimated Cost of Explosion Vessel

The cost of the explosion vessel system is estimated based on the current price stainless steel and the other items are based on current market price.

Table 5.6: The estimated cost of the explosion vessel and the auxiliary items.

Item	Quantity	Estimated Price	Company
1. Body, fan and saddle support of explosion vessel		RM 7,000 (Raw Material)	Based on current metal prices (www.meps.co.uk.com)
2. Optical Glasses	2	RM 1,200	Sciner Company
3. Flanges and bolt	2	RM 900	Aalco Company
3. Needle Valve	1	RM 350	Imperial Company
4. Other valves	4	RM 1,500	Swagelok Company
6. Motors for fan	4	RM 3,000	Remx Company
7. Heating Coil	1	RM 1,300	Heatrex Company
8. Pressure Transducer	1	RM 1,800	Omega Company
9. Thermocouple	1	RM 1,100	Chentronics Company
10. Data acquisition system	1	RM 5,500	National Instruments
TOTAL		RM 23,650	

The price is not really accurate since for the body, the price is just for the raw material without fabrication. For the other items, the price can be different because of the inflation rate and the delivery cost of material.

For cost of fabrication and assemble, it is estimated about RM 2,000. The total sum for the whole system is estimated around RM 25,650.

CHAPTER 6

CONCLUSION AND RECOMMENDATION

This final year project describes about the design of an explosion vessel and the auxiliary items required. The project was executed on scheduled and the objective to design a constant volume explosion vessel for fundamental study of flames and combustion has been achieved.

The design is basically based on the related literature review and the ASME standards codes to ensure the reliability of the explosion vessel during the operations. The technical drawings produced are based on the calculations and safety standards. Further contingencies have been added to ensure that the explosion vessel works safely. The calculations and the material selections are done based on the theoretical calculations and there is no way to certify that this experimental equipment would work properly until the prototype has been fabricated and tested. Taking in consideration the requirements of impact testing, it is found that the impact testing is not necessary for the explosion vessel based on the Minimum Metal Design Temperature (MDMT) procedure. A suggested inspection to be implemented on the fabricated explosion vessel is the ultrasonic inspection.

The recommendation for this project in the future is to fabricate and calibrate the vessel and the auxiliary items required in explosion equipments. Then the inspection and testing can be performed on the prototype. Modifications can be done to ensure that the explosion vessel is working as desired.

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DESIGN PROPERTIES		
1.	DESIGN PRESSURE	3284.75 kPa
2.	DESIGN TEMPERATURE	2641.4 kPa
3.	CORROSION ALLOWANCE	3 mm
4.	JOINT EFFICIENCY	1
5.	INSIDE DIAMETER	305 mm

GENERAL NOTES

1. VESSEL ARE DESIGNED ACCORDING TO ASME VIII DIVISION 1
3. ALL WELD TO BE 100% RADIOGRAPHED
2. ALL DIMENSION ARE IN MM

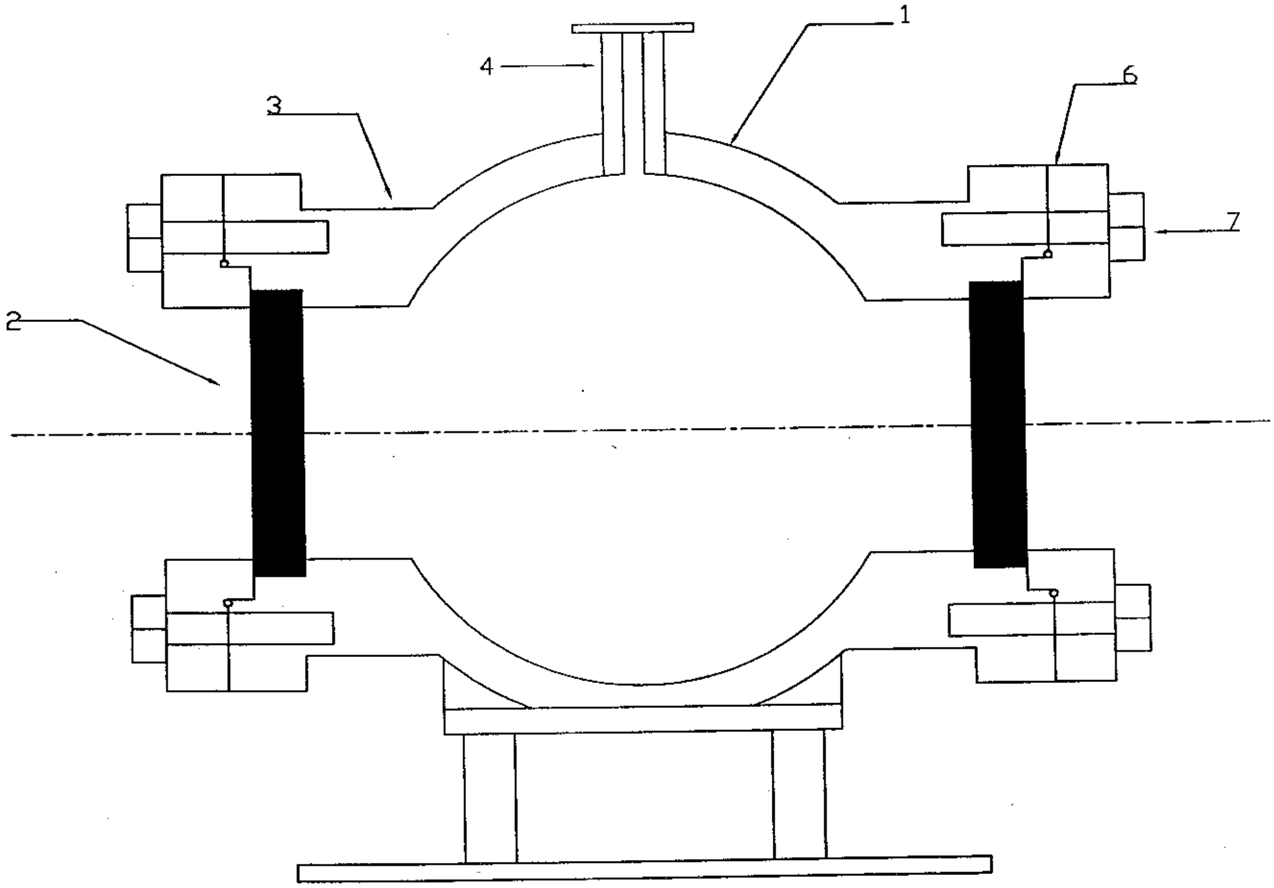
BILL OF MATERIAL

NO	DESCRIPTIONS	UNIT
1.	VESSEL BODY	1
2.	OPTICAL ACCESS	2
3.	NOZZLE OF OPTICAL ACCESS	2
4.	NOZZLE FOR INPUT AND OUTPUT	1
5.	FLANGE	4
6.	FLANGE	2
7.	BOLT	16
8.	CRADLE	2
9.	SADDLE	4
10.	PLATE BASE	1

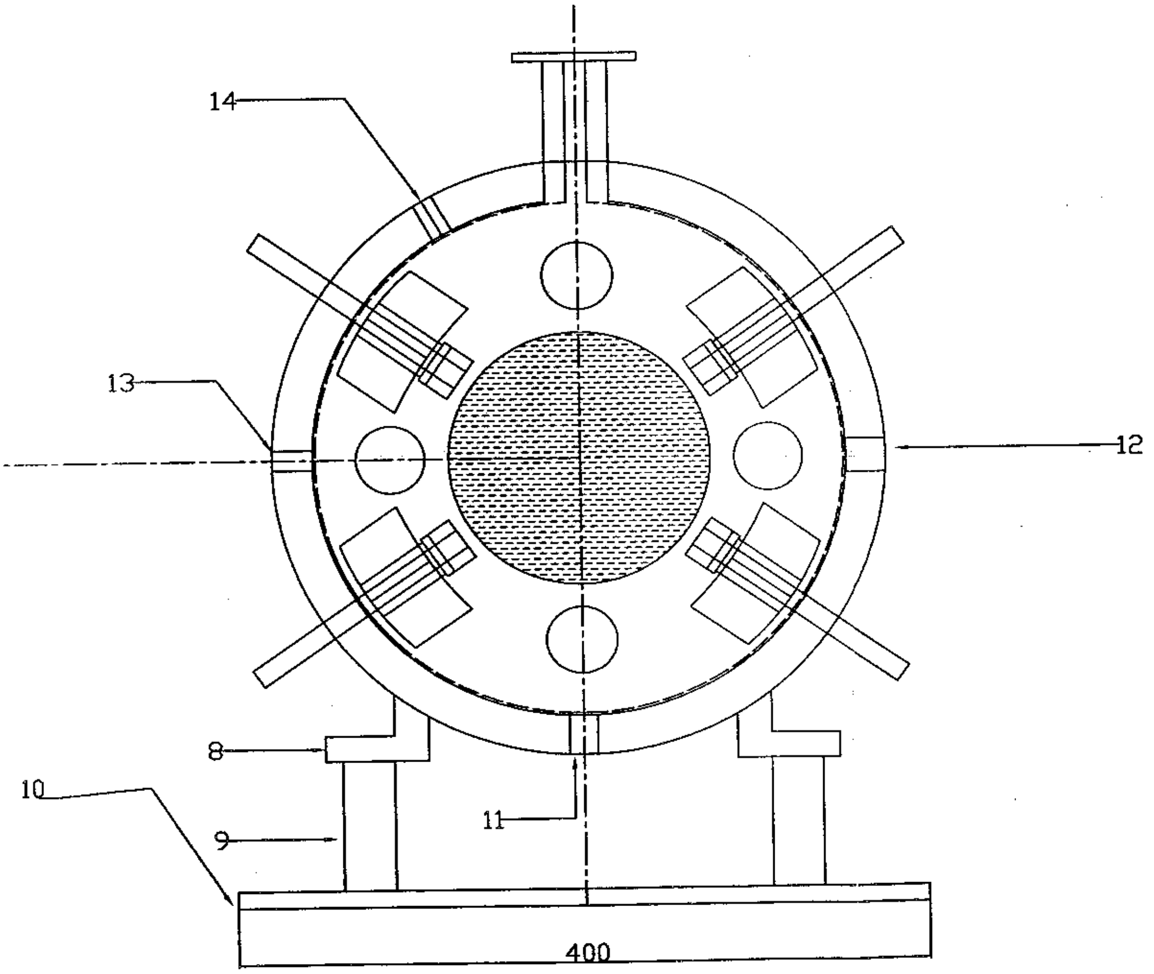
PROJECT
DESIGN OF EXPLOSION VESSEL FOR FLAME PROPAGATIONS
TITLE
GENERAL NOTES FOR EXPLOSION VESSEL

DRAWN BY	SCALE	DATE	DRAWING NO.
HAMIZAH	NTS	APRIL 209	NOTES

BILL OF MATERIAL		
NO	DESCRIPTIONS	UNIT
1	VESSEL BODY	1
2	OPTICAL ACCESS	2
3	NOZZLE OF OPTICAL ACCESS	2
4	NOZZLE FOR INPUT AND OUTPUT	1
5	FAN	4
6	FLANGE	2
7	BOLT	16
8	CRADLE	2
9	SADDLE	4
10	PLATE BASE	1
11	HOLE FOR SPARK IGNITOR	1
12	HOLE FOR PRESSURE TRANSDUCER	1
13	HOLE FOR THERMOCOUPLE	1
14	HOLE FOR NEEDLE VALVE	1



SIDE VIEW OF EXPLOSION VESSEL



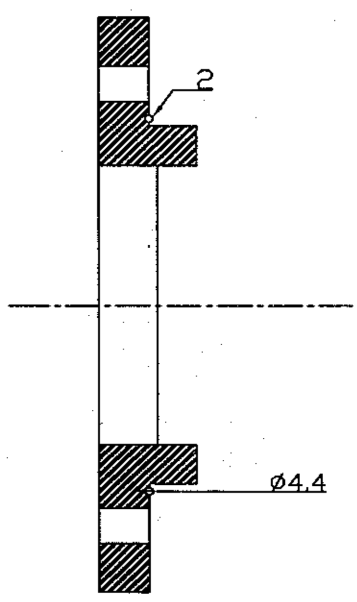
FRONT VIEW OF EXPLOSION VESSEL

PROJECT
DESIGN OF THE EXPLOSION VESSEL
FOR FLAME PROPAGATIONS

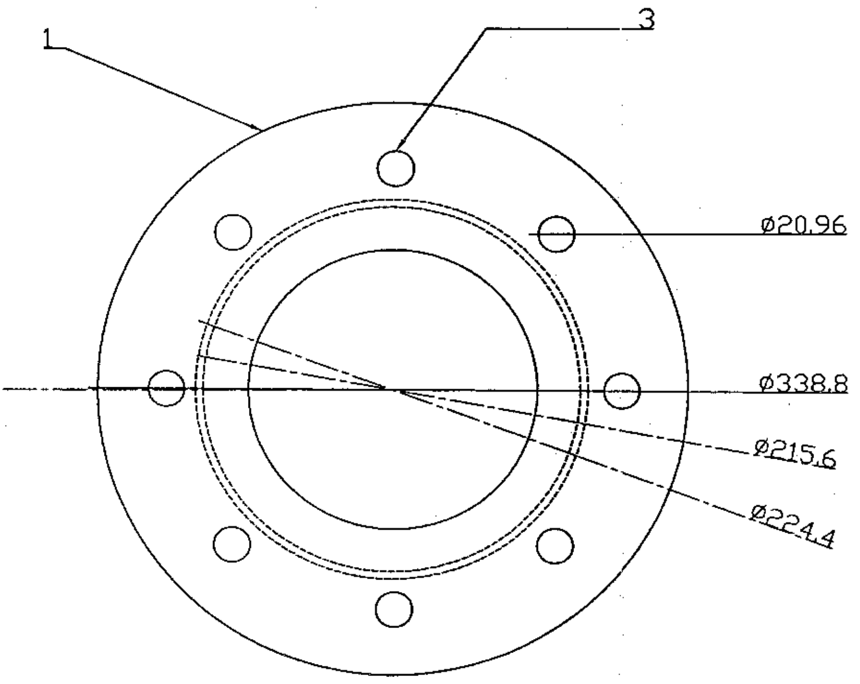
TITLE
THE SIDE VIEW AND THE FRONT VIEW
OF THE EXPLOSION VESSEL

DRAWN BY	UNIT	SCALE	DATE	DRAWING NO.
HAMIZAH	mm	1:5	MARCH 09	DRAWING A

BILL OF MATERIAL		
NO	DESCRIPTIONS	UNIT
1	FLANGE	2
2	O RING	2
3	HOLE FOR BOLT	16



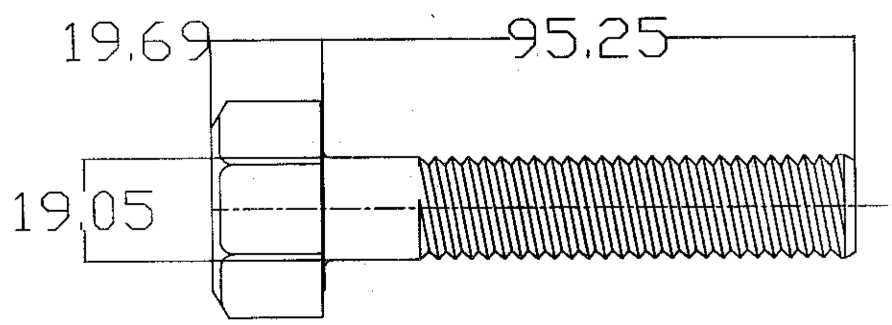
SIDE VIEW OF FLANGE



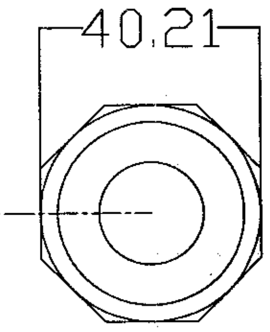
FRONT VIEW OF FLANGE

PROJECT
DESIGN OF THE EXPLOSION VESSEL
FOR FLAME PROPAGATIONS
TITLE
THE SIDE VIEW AND THE FRONT VIEW
OF FLANGE FOR THE EXPLOSION VESSEL

DRAWN BY	UNIT	SCALE	DATE	DRAWING NO.
HAMIZAH	mm	1:5	MARCH 09	DRAWING B



SIDE VIEW OF BOLT

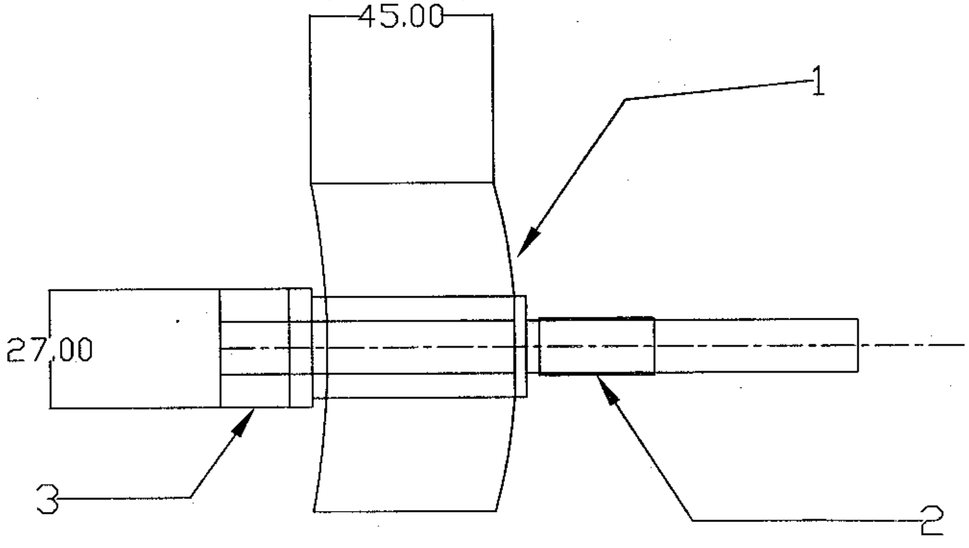


PLAN VIEW OF BOLT

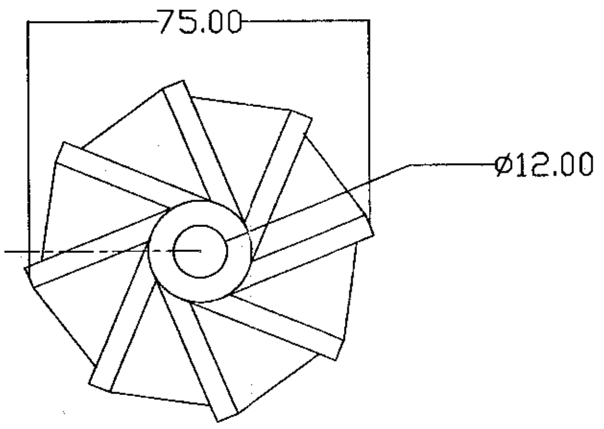
PROJECT
DESIGN OF THE EXPLOSION VESSEL
FOR FLAME PROPAGATIONS
TITLE
THE SIDE VIEW AND THE PLAN VIEW
OF THE BOLT FOR THE EXPLOSION VESSEL

DRAWN BY	UNIT	SCALE	DATE	DRAWING NO.
HAMIZAH	mm	1:1.5	MARCH 09	DRAWING C

BILL OF MATERIAL		
NO	DESCRIPTIONS	UNIT
1	FAN	4
2	WEAR SLEEVE	4
3	NUT WITH CAP	4



SIDE VIEW OF FAN

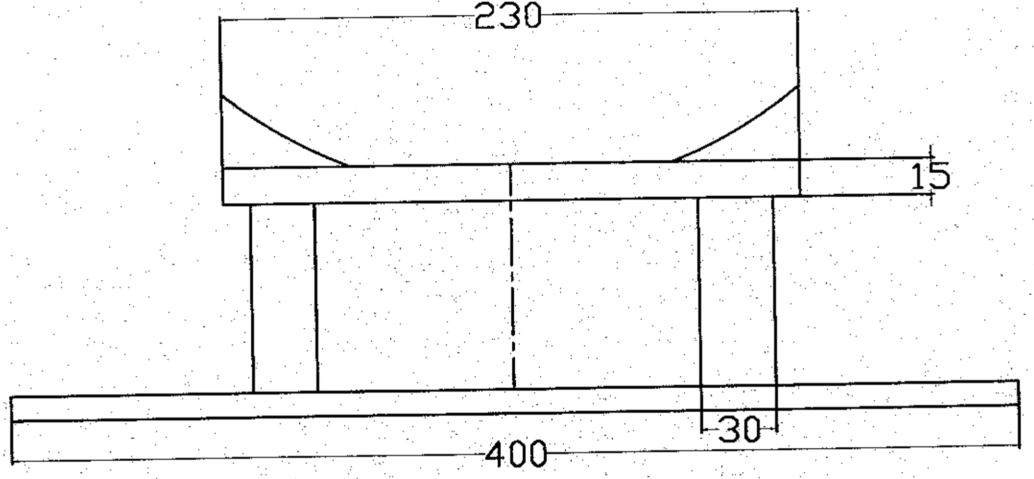


PLAN VIEW OF FAN

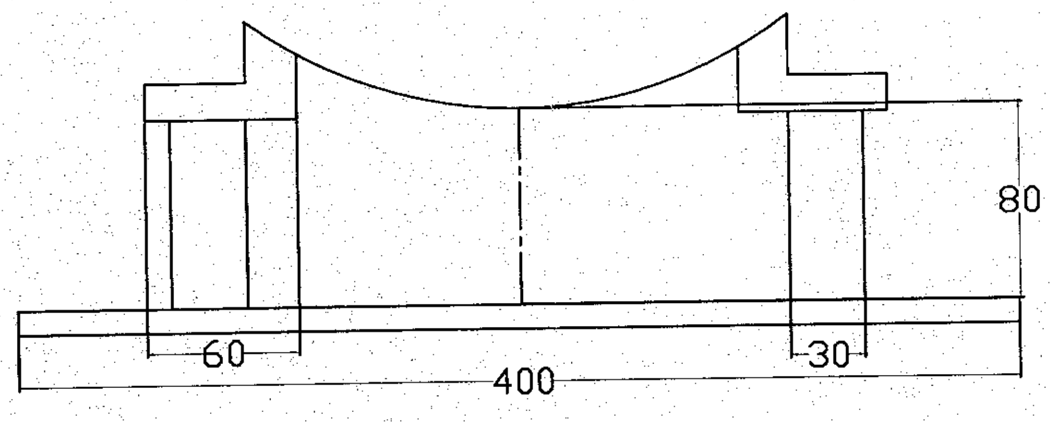
PROJECT
DESIGN OF EXPLOSION VESSEL FOR FLAME PROPAGATIONS
TITLE
DRAWING FAN IN THE EXPLOSION VESSEL

DRAWN BY	UNIT	SCALE	DATE	DRAWING NO.
HAMIZAH	mm	1:1.8	APRIL 2009	DRAWING D

BILL OF MATERIAL		
NO	DESCRIPTIONS	UNIT
1	CRADLE	2
2	SADDLE SUPPORT	4
3	BASE SUPPORT	1



SIDE VIEW OF CRADLE AND SADDLE SUPPORT



FRONT VIEW OF CRADLE AND SADDLE SUPPORT

PROJECT :
DESIGN OF THE EXPLOSION VESSEL
FOR FLAME PROPAGATIONS

TITLE
CRADLE AND SADDLE SUPPORT
OF THE EXPLOSION VESSEL

DRAWN BY	UNIT	SCALE	DATE	DRAWING NO.
HAMIZAH	mm	1: 3.3	MARCH 09	DRAWING E

APPENDIX 1

The Factor of Safety According to ASME Guidelines

Table A1: Factor of Safety Based on ASME Guidelines. Reproduced from Fryer (1998).

ASME Code Section	Factor of Safety	Basis	
		Theory of Failure	Material Property
Section VIII-3, Pressure Vessels	2	Distortion Energy	Material yield strength first reached throughout wall thickness
Section III, Nuclear Components, and Section VIII-2, Pressure Vessels	3	Maximum Shear	Average shear stress in wall thickness reaches material ultimate tensile strength
Section I, Power Boilers and Section VIII-I, Pressure Vessels	3.5	Maximum Stress	Average tensile stress in wall thickness reaches material ultimate tensile strength
Section IV, Heating Boilers	5	Maximum Stress	Average tensile stress in wall thickness reaches material ultimate tensile strength

APPENDIX 2

Figure A1: Gantt Chart for The Design of The Explosion Vessel for Flame Propagations for Semester 1.

ACTIVITY/ Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Selection of Proposed Topic	■													
Topic Award		■												
Preliminary Research and Reading			■	■										
Submission of Preliminary Report				□										
First Estimation and Early Design					■									
Identifying Suitable Codes Standard						■								
Material Selection of Vessel Body							■	■	■					
Submission of Progress Report								□						
Starting Design the Schematic Drawing of System										■	■			
Final Design and Detail Report												■	■	
Submission of Interim Report														□
Oral Presentation														□

■ Progress

□ Project Milestone

APPENDIX 3

Figure A2: Gantt Chart for the Design of the Explosion Vessel for Flame Propagations for Semester 2.

ACTIVITY/ Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Design the body of explosion vessel	■													
Design of flanges and nuts of The Vessel		■	■											
Submission of Progress Report				□										
Starting the technical drawing					■									
Identify the auxiliary items of system						■	■							
Design fan and the saddle support								■						
Find the suitable seal for the vessel								■						
Seminar									□					
Poster Exhibition										□				
Technical drawing of the vessel											■	■		
Submission of Dissertation (soft bound)														□

■ Progress

□ Project Milestone

APPENDIX 4

Calculation of Thickness of Wall Vessel

Taking a specific material, Stainless steel 316, the calculation of the shell thickness is shown as below:

Design Properties:

The GasEQ calculation yield that the value of maximum pressure is 938.5KPa, and the value will be multiplied with the safety design factor outlined by ASME Section VIII Divisions 1, about 3.5.

Design Pressure = 3754 KPa

Design Temperature = 2641.4 K

Material specification:

Tensile Strength = 515,000 KPa

Internal radius in corroded condition

$R=R_{in}+C.A$

$=152.2\text{mm} + 3\text{ mm}$

$=155.5\text{ mm}$

Joint Coefficient = 1 for fully radiograph

Corrosion Allowance = 3mm

For vessel thickness, the calculation is using the equation in ASME guidelines:

$$t = \frac{PR}{2SE - 0.2P} + C.A$$

Then, the value will be added with the corrosion allowance:

$$t = \frac{3754kN/m^2 \times 0.1555}{(2 \times 515{,}000kN/m^2 \times 1) - (0.2 \times 938.5kN/m^2)} + 0.003mm$$

$$t = 3..567 \times 10^{-3} m$$

$$t = 3.6mm$$

The nominal thickness is determined, based on the previous literature review, where the calculated thickness of nozzle is multiply with safety factor for further contingencies.

Nominal Thickness $= t_{rn} \times 7$

= 3.15 mm x 7

=25 mm

In order to ensure the material can be used for the equation, the validation of the formula is determined by using the tensile strength of the material:

0.385 SE > P

0.385 x 515,000 x 1 > 3754 kPa

198275 > 3754 kPa

Thus, the analysis above is valid

APPENDIX 5

Calculation of Nozzle Thickness for Optical Accesses

Shell Material		: 316
Nozzle Material		: 304 L
Allowable Shell Stress	Sv	: 515 MPa
Allowable Nozzle Stress	S_n	: 500 MPa
Design Pressure		: 3754 KPa
Corrosion Allowance	CA	: 3mm
Nozzle Joint Efficiency	E	: 1

Nozzle properties:

Inside diameter = 150 mm

Inside radius = 75 mm

Nozzle thickness is calculated using the ASME equation for nozzle thickness:

$$t_{rn} = \frac{PR_n}{SE - 0.6P}$$

The value then added with the corrosion allowance

$$t_{rn} = \frac{3754kPa \times 0.075m}{(500{,}000kPa \times 1) - (0.6 \times 3754kPa)} + 3mm$$

=3.56 mm

Where t_{rn} = calculated thickness of nozzle with corrosion factor.

The nominal thickness is determined, based on the previous literature review, where the calculated thickness of nozzle is multiply with safety factor for further contingencies.

Nominal Thickness $= t_{rn} \times 7$

$= 3.14$ mm x 7

$=25$ mm

The next calculation is to determine whether the reinforcement element is needed for the nozzle. To do that, we first check whether the nozzle opening is adequately reinforced. If the sum of several areas is more than the area of reinforcement area, the reinforcement element is not needed.

Check without reinforcement element

Strength reduction factor

$f_{r,1} = f_{r,2} = f_{r,2} = S_n/S_v$

$= 0.97$

Correction factor, $F=1$

Area of reinforcement required

$A = dt_rF$

$= (0.15)(0.025)(1)$

$= 3.75 \text{ x}10^{-3} \text{ m}^2$

$A = 3750 \text{ mm}^2$

Area of reinforcement required is 3750 mm²

Calculate available area in shell (larger)

$A_{11} = d\,(E_1t\text{-}F_{tr})$

$= (0.15)[1(0.030) - 1(0.025)]$

$= 7.5 \text{ x}10^{-4}$

$= 750 \text{ mm}^2$

$A_{12} = 2\,(t+t_n)\,(E_{1t} - F_{tr})$

$= 6\text{x } 10^{-5}\text{m}^2$

$= 60\text{mm}^2$

Thus, use $A_{11} = 750\ \text{mm}^2$

Area available in outward nozzle (smaller)

$A_{21} = (t_n - t_m)\ 5t$

$= (0.024 - 3.14 \times 10^{-3})\ 5(0.03)$

$= 3.129 \times 10^{-3}\ \text{m}^2$

$= 3129\ \text{mm}^2$

$A_{22} = 2(t_n - t_m)(2.5\ t_n + t_m)$

$= 2(0.024 - 3.14 \times 10^{-3})(2.5(0.024))$

$= 2503.2\ \text{mm}^2$

Thus, for A_{21} use 2503.2 mm^2

Area available in inward or protruding nozzle

Protruding length, h (smaller)

$h = 2.5\ t$

$= 2.5\ (0.03)$

$= 0.075\ \text{m}$

$h = 2.5\ t$

$= 2.5\ (0.025)$

$= 0.0625\text{m}$

$A_3 = 2(t_n - c)\ f_{r2}h$

$= 2(0.024 - 0.003)(0.97)$

$= 0.04074\ \text{m}^2$

$= 40740\ mm^2$

Thus, area available in inward or protruding nozzle, A_3 is 40740 m

Area available in weld

$A_{41} \quad = 2x\ 0.5\ x\ (leg)^2\ x\ f_{r2}$

Where taking fillet weld, $t_w = 0.7\ t_{min}$

Note that actual fillet weld is between range $0.7t_{min} < t_{actual} < t_{min}$

$A_{41} \quad = 2\ x\ 0.5\ x\ (0.024)^2\ x\ (0.97)$

$= 5.5872\ x\ 10^{-4} m^2$

$= 558.72\ mm^2$

Area available in weld, $A_{41} = 558.72\ mm^2$

Area provided $= A_1 + A_2 + A_3 + A_4$

$= 750\ mm^2 + 2503.2\ mm^2 + 40740\ mm^2 + 558.72\ mm^2$

$= 44551.72\ mm^2$

Since $A_1 + A_2 + A_3 + A_4 > A$, opening is adequately reinforced.

No reinforcing element needed.

APPENDIX 6

Calculation of Nozzle for Input and Output

Shell Material		: 316
Nozzle Material		: 304 L
Allowable Shell Stress	Sv	: 515 MPa
Allowable Nozzle Stress	S_n	: 500 MPa
Design Pressure		: 3754 KPa
Corrosion Allowance	CA	: 3mm
Nozzle Joint Efficiency	E	: 1

Nozzle properties:

Inside diameter = 12 mm

Inside radius = 6 mm

$t_r = 3.15 \text{ x } 10^{-3}$ m

t = 0.025 m

$t_m = 3 \text{ x } 10^{-3}$m

$t_n = 0.024$ m

Nozzle thickness is calculated using the ASME equation for nozzle thickness:

$$t_m = \frac{PR_n}{SE - 0.6P}$$

The value then added with the corrosion allowance.

$$t_m = \frac{3754kPa \times (6x10^{-3})m}{(500{,}000kPa \times 1) - (0.6 \times 37545kPa)} + 0.003m$$

$= 4.525\text{x}10^{-5}$ m+ 0.003 m

= 3 mm

Where t_{rn} = calculated thickness of nozzle with corrosion factor.

The nominal thickness is determined, based on the previous literature review, where the calculated thickness of nozzle is multiply with safety factor for further contingencies.

Nominal Thickness $= t_{rn} x4$

$= 3.04$ mm x 4

$=12$ mm

The next calculation is to determine whether the reinforcement element is needed for the nozzle. To do that, we first check whether the nozzle opening is adequately reinforced. If the sum of several areas is more than the area of reinforcement area, the reinforcement element is not needed.

Check without reinforcement element

Strength reduction factor

$f_{r,1} = f_{r,2} = f_{r,2} = S_n/S_v$

$= 0.97$

Correction factor, $F=1$

Area of reinforcement required

$A = dt_rF$

$= (0.012)(0.00315)(1)$

$= 3.78 \text{ x}10^{-5} \text{ m}^2$

$A = 37.8 \text{ mm}^2$

Area of reinforcement required is 37.8 mm^2

Calculate available area in shell (larger)

$A_{11} = d\ (E_1t\text{-}F_{tr})$

$= (0.012)[1(0.025) - 1(0.00315)]$

$= 2.622 \times 10^{-4} m^2$

$= 262.2 mm^2$

$A_{12} = 2(t+t_n)(E_{1t} - F_{tr})$

$= 2(0.025 + 0.024)[(1)(0.025)-(1)(0.00315)]$

$= 2.1413 \times 10^{-3} m^2$

$= 2141.3 mm^2$

Thus, use $A_{11} = 2141.3 mm^2$

Area available in outward nozzle (smaller)

$A_{21} = (t_n - t_m) 5t$

$= (0.024 - 3 \times 10^{-3}) 5(0.03)$

$= 3.149 \times 10^{-3} m^2$

$= 3149 mm^2$

$A_{22} = 2(t_n - t_m)(2.5 t_n + t_m)$

$= 2(0.024 - 3 \times 10^{-3})(2.5(0.024))$

$= 2.519 \times 10^{-3} m^2$

$= 2519.99 mm^2$

Thus, for A_{21} use 2519.99 mm^2

Area available in inward or protruding nozzle

Protruding length, h

$h = 2.5 t$

$= 2.5 (0.025)$

$= 0.0625 m$

$h = 2.5\ t$

$= 2.5\ (0.024)$

$= 0.06\ m$

Take the protruding length 0.0625 m

$A_3 \quad = 2(t_n - c)\ f_{r2}h$

$= 2(0.024-0.003)\ (0.97)\ (0.06)$

$= 2.444\ x10^{-3}\ m^2$

$= 2444.4\ mm^2$

Thus, area available in inward or protruding nozzle, A_3 is 40740 m

Area available in weld

$A_{41} \quad = 2x\ 0.5\ x\ (leg)^2\ x\ f_{r2}$

Where taking fillet weld, $t_w = 0.7\ t_{min}$

Note that actual fillet weld is between range $0.7t_{min} < t_{actual} < t_{min}$

$A_{41} \quad = 2\ x\ 0.5\ x\ (0.024)^2\ x\ (0.97)$

$= 5.5872\ x\ 10^{-4} m^2$

$= 558.72\ mm^2$

Area available in weld, $A_{41} = 558.72\ mm^2$

Area provided $= A_1 + A_2 + A_3 + A_4$

$= 2141.3\ mm^2 + 2519.99\ mm^2 + 2444.4\ mm^2 + 558.72\ mm^2$

$= 7664.41\ mm^2$

Since $A_1 + A_2 + A_3 + A_4 > A$, opening is adequately reinforced.

Thus, no reinforcing element needed.

APPENDIX 7

The Material Properties for Observing Windows (Fused Silica)

Table A2: Material Properties for Fused Silica, SiO_2.
Reproduced from Sciner Company (2009)

Parameter	Value
Refractive Index	n_f (486nm) = 1.4631; n_d (588nm) = 1.4585; n_c (656nm) = 1.4564
Birefringence Constant	3.54 (nm/cm)/(kg/cm^2)
Abbe Constant	67.8
SSFluorescence	Virtually fluorescence free
Impurity Content	Total metallic impurities: approximately 5 ppm
Density	2.201 g/cm^3
Specific Heat Capacity	703 J Kg^{-1}K^{-1}
Thermal Conductivity	1.38 Wm^{-1}K^{-1}
Coefficient of Expansion	0.55 x 10^{-6} /°C
Softening Point	1600°C (2912°F)
Annealing Point	1120°C (2048°F)
Strain Point	1025°C (1877°F)
Max. Service Temperature	950°C (1742°F) - continuous, 1200°C (2192°F) - limited time
Dielectric Constant	3.91 at 1kHz
Dielectric Strength	250-400 kV/cm at 20°C
Young's Modulus	73 GPa at 25°C
Shear Modulus	31 GPa at 25°C
Rupture Modulus	50 MPa at 25°C
Bulk Modulus	36.9 GPa at 25°C
Apparent Elastic Limit	55MPa (7980 psi)
Compressive Strength	1.1 GPa
Tensile Strength	50 MPa
Poisson Ratio	0.17 at 25°C
Knoop Hardness	500 kg/mm^2
Molecular Weight	28.09
Class/Structure	Amorphous glass
Chemical Stability	High resistance to water and acids (except hydrofluoric).

APPENDIX 8

The Material Selection of Bolts

Table A3: The Material Selection of Heat Treated Bolts. Reproduced from Americanfastener Company (2009)

Grade	Diameter, in.	Min tempering temp F	Tensile strength min psi	Yield point min psi	Elongation in 2 in. min pct	Reduction of area min pct
A354 Grade BC	2-1/2 and under Over 2-1/2 to 4 incl.	850	125,000	109,000	16	50
A354 Grade BD	1-1/2 and under	850	115,000	99,000	16	45
A193 Grade B7 Chromium-Molybdenum	2-1/2 and under Over 2-1/2 to 4 incl. Over 4 to 7 incl.	850	150,000	125,000	14	35
A193 Grade B16 Chromium-Molybdenum-Vanadium	2-1/2 and under	1100	125,000	105,000	16	50
	Over 2-1/2 to 4 incl.	1100	115,000	95,000	16	50
	Over 4 to 7 incl.	1100	100,000	75,000	18	50
A320 Grade L7 Chromium-Molybdenum	2-1/2 and under	--	125,000	105,000	16	50
A320 Grade L43 Nickel-Chromium-Molybdenum	4 and under	--	125,000	105,000	16	50

Commonly used are the following grades of heat-treated alloy steel for high-pressure or extreme temperature service in diameters of 1/2 in. to 2 in., inclusive. Other grades and other diameters are available on special order.

ASTM A354, Grades BC and BD - heat-treated alloy steels for applications at normal atmospheric temperatures where high strength is required.

ASTM A193, Grade B7 - a heat-treated chromium-molybdenum steel widely used for medium high-temperature service.

ASTM A193, Grade B16 - a heat-treated chromium-molybdenum-vanadium steel for high-pressure, high-temperature service.

ASTM A320, Grade L7 - This grade is intended for low-temperature service down to minus 150°F and has a minimum Charpy impact value of 15 ft-lb at this temperature. Sizes 2-1/2 in. and under.

ASTM A320, Grade L43 - The same properties offered by Grade L7 in sizes up to 2-1/2 are obtainable up to 4 in. in Grade L43.

Table A4: The elements in A193 Grade B16. Reproduced from Americanfastener Company (2009)

Elements	A193 Grade B16 Chromium-Molybdenum-Vanadium	
	Range percent	Check variation over or under percent
Carbon...	0.36-0.44	0.02
Manganese...	0.45-0.70	0.03
Phosphorus, max...	0.04	0.005 over
Sulphur, max...	0.04	0.005 over
Silicon...	0.20-0.35	0.02
Chromium...	0.80-1.15	0.05
Molybdenum...	0.50-0.65	0.03
Vanadium...	0.25-0.35	0.03

APPENDIX 9

Table A3: The dimensional data for Bolts and Flanges (Moss, 2004).

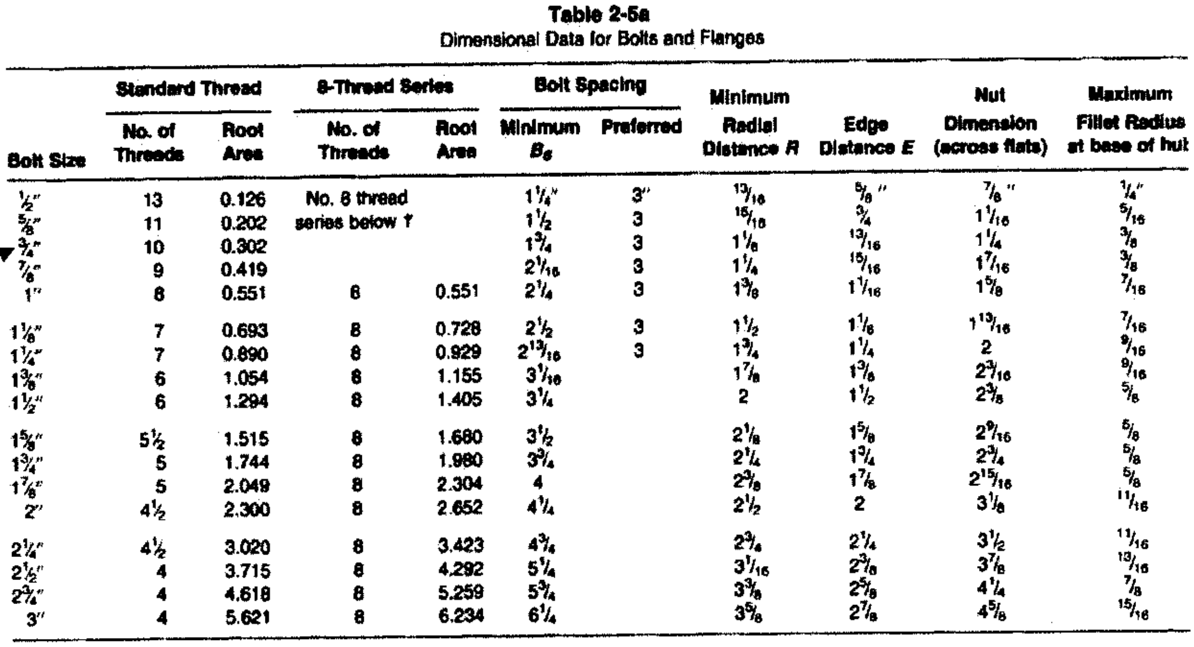


Table 2-5a
Dimensional Data for Bolts and Flanges

Bolt Size	Standard Thread: No. of Threads	Standard Thread: Root Area	8-Thread Series: No. of Threads	8-Thread Series: Root Area	Bolt Spacing: Minimum B_s	Bolt Spacing: Preferred	Minimum Radial Distance *R*	Edge Distance *E*	Nut Dimension (across flats)	Maximum Fillet Radius at base of hut
½″	13	0.126	No. 8 thread series below 1″		1¼″	3″	13/16	5/8″	7/8″	1/4″
⅝″	11	0.202			1½	3	15/16	3/4	1 1/16	5/16
¾″	10	0.302			1¾	3	1⅛	13/16	1¼	3/8
⅞″	9	0.419			2 1/16	3	1¼	15/16	1 7/16	3/8
1″	8	0.551	8	0.551	2¼	3	1⅜	1 1/16	1⅝	7/16
1⅛″	7	0.693	8	0.728	2½	3	1½	1⅛	1 13/16	7/16
1¼″	7	0.890	8	0.929	2 13/16	3	1¾	1¼	2	9/16
1⅜″	6	1.054	8	1.155	3 1/16		1⅞	1⅜	2 3/16	9/16
1½″	6	1.294	8	1.405	3¼		2	1½	2⅜	5/8
1⅝″	5½	1.515	8	1.680	3½		2⅛	1⅝	2 9/16	5/8
1¾″	5	1.744	8	1.980	3¾		2¼	1¾	2¾	5/8
1⅞″	5	2.049	8	2.304	4		2⅜	1⅞	2 15/16	5/8
2″	4½	2.300	8	2.652	4¼		2½	2	3⅛	11/16
2¼″	4½	3.020	8	3.423	4¾		2¾	2¼	3½	11/16
2½″	4	3.715	8	4.292	5¼		3 1/16	2⅜	3⅞	13/16
2¾″	4	4.618	8	5.259	5¾		3⅜	2⅝	4¼	7/8
3″	4	5.621	8	6.234	6¼		3⅝	2⅞	4⅝	15/16

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Table A4: Number and size of Bolts for Flanged Joints (Moss, 2004).

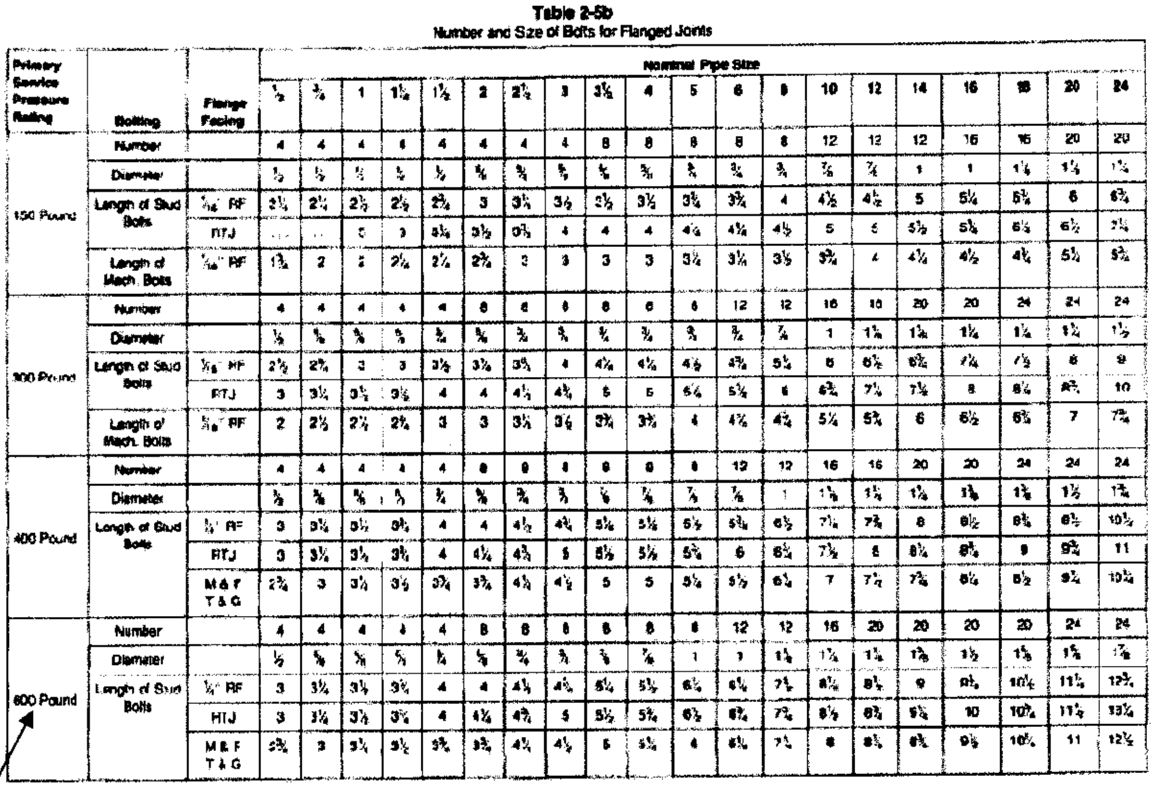

Table 2-5b
Number and Size of Bolts for Flanged Joints

Primary Service Pressure Rating	Bolting	Flange Facing	Nominal Pipe Size																			
			½	¾	1	1¼	1½	2	2½	3	3½	4	5	6	8	10	12	14	16	18	20	24
150 Pound	Number		4	4	4	4	4	4	4	4	8	8	8	8	8	12	12	12	16	16	20	20
	Diameter		½	½	½	½	½	⅝	⅝	⅝	⅝	⅝	¾	¾	¾	⅞	⅞	1	1	1⅛	1⅛	1¼
	Length of Stud Bolts	1/16″ RF	2¼	2¼	2½	2½	2¾	3	3¼	3½	3½	3½	3¾	3¾	4	4½	4½	5	5¼	5¾	6	6¾
		RTJ	...	...	3	3	3¼	3½	3¾	4	4	4	4¼	4¼	4½	5	5	5½	5¾	6¼	6½	7¼
	Length of Mach. Bolts	1/16″ RF	1¾	2	2	2¼	2¼	2¾	3	3	3	3	3¼	3¼	3½	3¾	4	4¼	4½	4¾	5½	5¾
300 Pound	Number		4	4	4	4	4	8	8	8	8	8	8	12	12	16	16	20	20	24	24	24
	Diameter		½	⅝	⅝	⅝	¾	⅝	¾	¾	¾	¾	¾	¾	⅞	1	1⅛	1⅛	1¼	1¼	1¼	1½
	Length of Stud Bolts	1/16″ RF	2½	2¾	3	3	3½	3¼	3¾	4	4¼	4¼	4½	4¾	5¼	6	6½	6¾	7¼	7½	8	9
		RTJ	3	3½	3½	3½	4	4	4½	4¾	5	5	5¼	5½	6	6¾	7¼	7½	8	8¼	8¾	10
	Length of Mach. Bolts	1/16″ RF	2	2½	2½	2¾	3	3	3¼	3½	3¾	3¾	4	4¼	4¾	5¼	5¾	6	6½	6¾	7	7¾
400 Pound	Number		4	4	4	4	4	8	8	8	8	8	8	12	12	16	16	20	20	24	24	24
	Diameter		½	⅝	⅝	⅝	¾	⅝	¾	¾	⅞	⅞	⅞	⅞	1	1⅛	1¼	1¼	1⅜	1⅜	1½	1¾
	Length of Stud Bolts	¼″ RF	3	3½	3½	3¾	4	4	4½	4¾	5¼	5¼	5½	5¾	6½	7¼	7⅝	8	8½	8¾	9½	10½
		RTJ	3	3½	3½	3¾	4	4¼	4¾	5	5½	5½	5¾	6	6¾	7½	8	8¼	8¾	9	9¾	11
		M & F T & G	2¾	3	3¼	3½	3¾	3¾	4¼	4½	5	5	5¼	5½	6¼	7	7½	7¾	8¼	8½	9¼	10¼
600 Pound	Number		4	4	4	4	4	8	8	8	8	8	8	12	12	16	20	20	20	20	24	24
	Diameter		½	⅝	⅝	⅝	¾	⅝	¾	¾	⅞	⅞	1	1	1⅛	1¼	1¼	1⅜	1½	1⅝	1⅝	1⅞
	Length of Stud Bolts	¼″ RF	3	3½	3½	3¾	4	4	4½	4¾	5¼	5½	6¼	6¾	7½	8½	8¾	9	9¾	10½	11¼	12¾
		RTJ	3	3½	3½	3¾	4	4¼	4¾	5	5½	5¾	6½	6¾	7¾	8½	8¾	9¼	10	10¾	11½	13¼
		M & F T & G	2¾	3	3¼	3½	3¾	3¾	4¼	4½	5	5¼	6	6½	7¼	8	8½	8¾	9½	10¼	11	12½

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APPENDIX 8

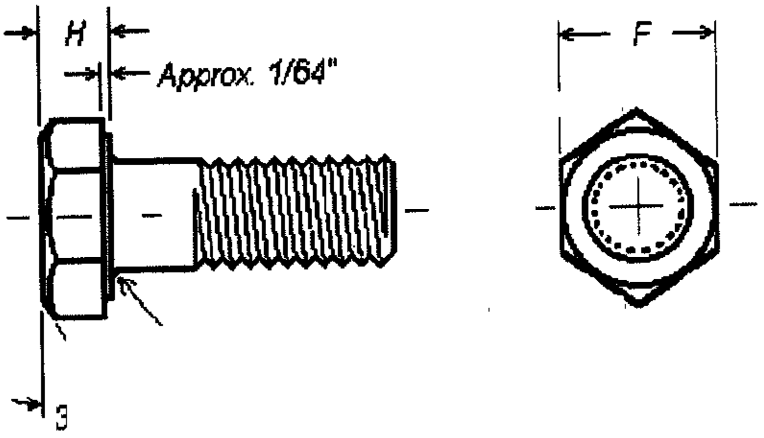


Figure A4: Nominal diameter of bolts and dimensions of head bolt (Kalpakjian, 2000)

Table A5: The nominal diameter and the dimensions of head of the bolts. Reproduced from Kalpakjian (2000).

Nominal Diameter (inches)	Across Flats (F) inches	Head Height (H) inches
¼ (0.25)	0.5000	5/32
5/16 (0.3125)	0.5625	13/64
3/8 (0.3750)	0.6875	15/64
7/16 (0.4375)	0.7500	9/32
1/2 (0.5000)	0.8125	5/16
9/16 (0.5625)	0.9375	23/64
5/8 (0.6250)	1.1250	25/64
3/4 (0.7500)	1.5850	31/40
7/8 (0.8750)	1.6875	33/40
1 (1.0000)	1.8750	11/16
1 1/8 (1.1250)	2.0625	25/32
1 1/4 (1.2500)	2.2500	27/32
1 3/8 (1.3750)	2.2375	15/26
1 1/2 (1.5000)	2.5000	17/26

APPENDIX 9

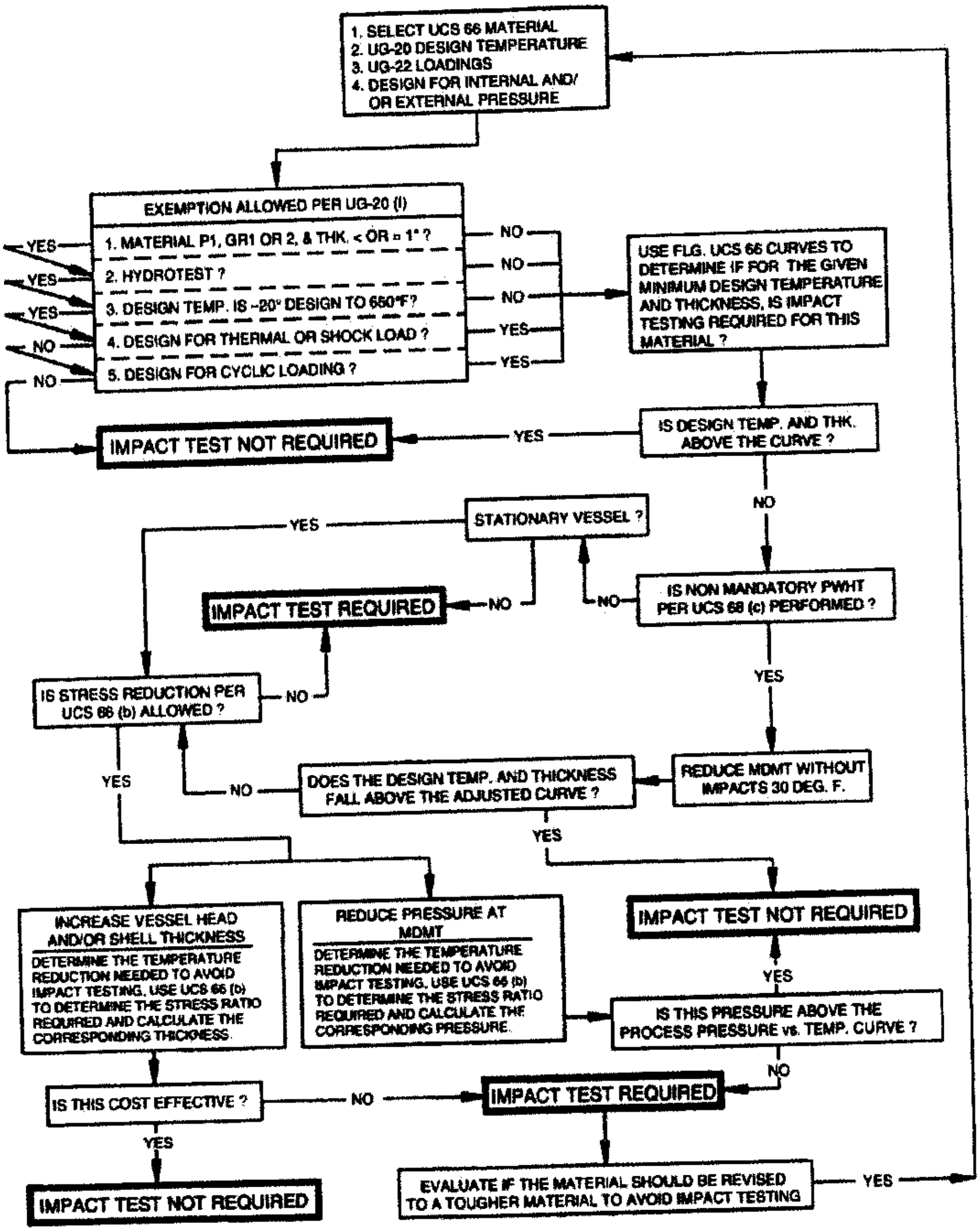


Figure A5: Flow chart showing decision-making process to determine MDMT and impact-testing requirements (Moss, 2004)

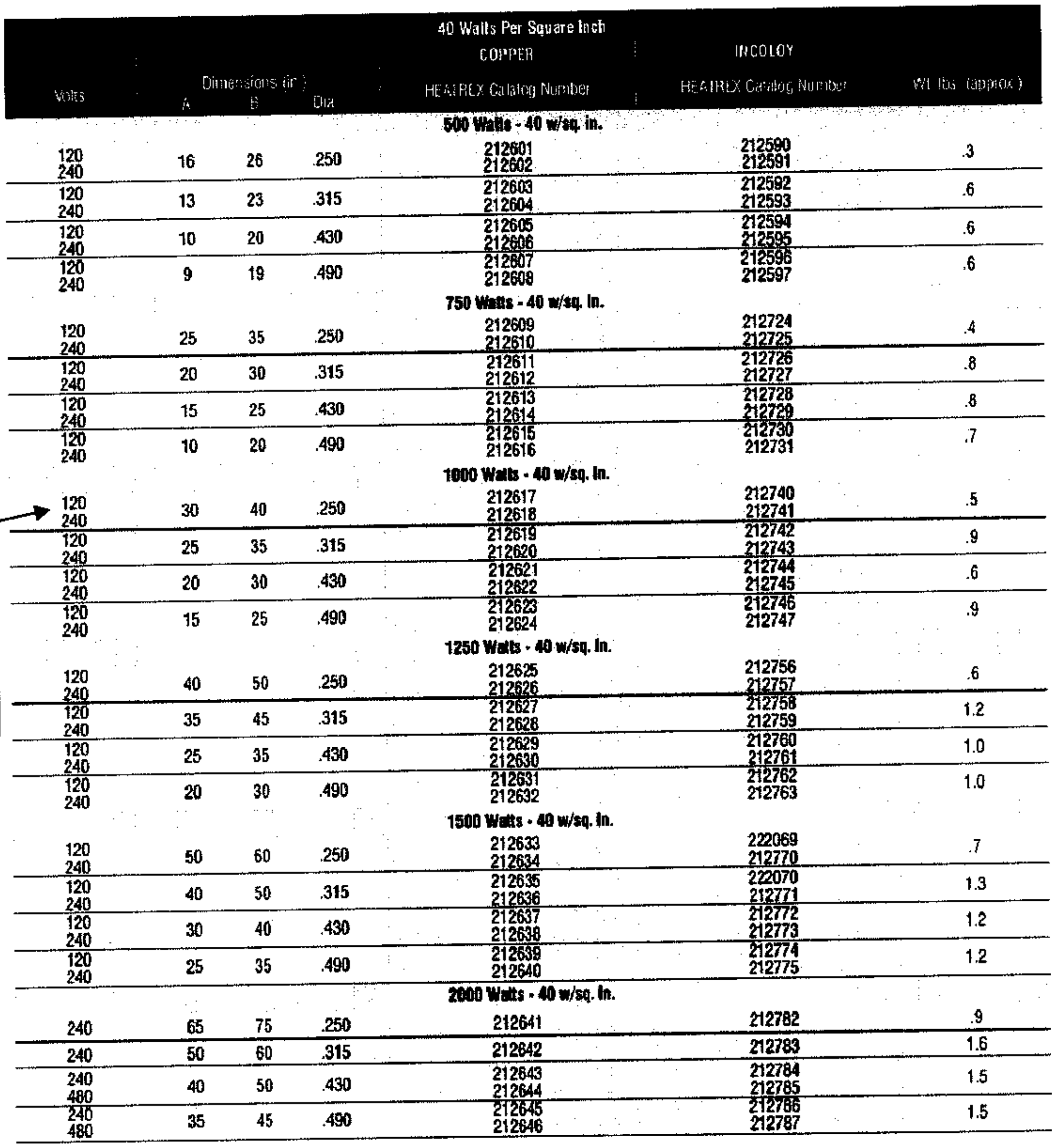
APPENDIX 10

Table A6: Types of thermocouple and the temperature range. Reproduced from Engineering Toolbox (2009)

Instrument	Temperature Range		Accuracy
	Recommended *(°F)*	Maximum *(°F)*	
Type J probes	32 to 1336	-310 to 1832	1.8 to 7.9°F or 0.4% of reading above 32°F, whichever is greater
Type K probes	32 to 2300	-418 to 2507	1.8 to 7.9°F or 0.4% of reading above 32°F, whichever is greater
Type T probes	-299 to 700	-418 to752	0.9 to 3.6°F or 0.4% of reading above 32°F, whichever is greater
Type E probes	32 to 1600	32 to 1650	1.8 to 7.9°F or 0.4% of reading above 32°F, whichever is greater
Type R probes	32 to 2700	32 to 3210	2.5°F or 0.25% of reading, whichever is greater
Type S probes	32 to 2700	32 to 3210	2.5°F or 0.25% of reading, whichever is greater

APPENDIX 11

Table A7: Guidelines for choosing heating coil of Copper and Incoloy (Heatrex, 2009)



Volts	Dimensions (in.)			40 Watts Per Square Inch COPPER HEATREX Catalog Number	INCOLOY HEATREX Catalog Number	Wt. lbs. (approx.)
	A	B	Dia			
				500 Watts - 40 w/sq. in.		
120 240	16	26	.250	212601 212602	212590 212591	.3
120 240	13	23	.315	212603 212604	212592 212593	.6
120 240	10	20	.430	212605 212606	212594 212595	.6
120 240	9	19	.490	212607 212608	212596 212597	.6
				750 Watts - 40 w/sq. in.		
120 240	25	35	.250	212609 212610	212724 212725	.4
120 240	20	30	.315	212611 212612	212726 212727	.8
120 240	15	25	.430	212613 212614	212728 212729	.8
120 240	10	20	.490	212615 212616	212730 212731	.7
				1000 Watts - 40 w/sq. in.		
120 240	30	40	.250	212617 212618	212740 212741	.5
120 240	25	35	.315	212619 212620	212742 212743	.9
120 240	20	30	.430	212621 212622	212744 212745	.6
120 240	15	25	.490	212623 212624	212746 212747	.9
				1250 Watts - 40 w/sq. in.		
120 240	40	50	.250	212625 212626	212756 212757	.6
120 240	35	45	.315	212627 212628	212758 212759	1.2
120 240	25	35	.430	212629 212630	212760 212761	1.0
120 240	20	30	.490	212631 212632	212762 212763	1.0
				1500 Watts - 40 w/sq. in.		
120 240	50	60	.250	212633 212634	222069 212770	.7
120 240	40	50	.315	212635 212636	222070 212771	1.3
120 240	30	40	.430	212637 212638	212772 212773	1.2
120 240	25	35	.490	212639 212640	212774 212775	1.2
				2000 Watts - 40 w/sq. in.		
240	65	75	.250	212641	212782	.9
240	50	60	.315	212642	212783	1.6
240 480	40	50	.430	212643 212644	212784 212785	1.5
240 480	35	45	.490	212645 212646	212786 212787	1.5

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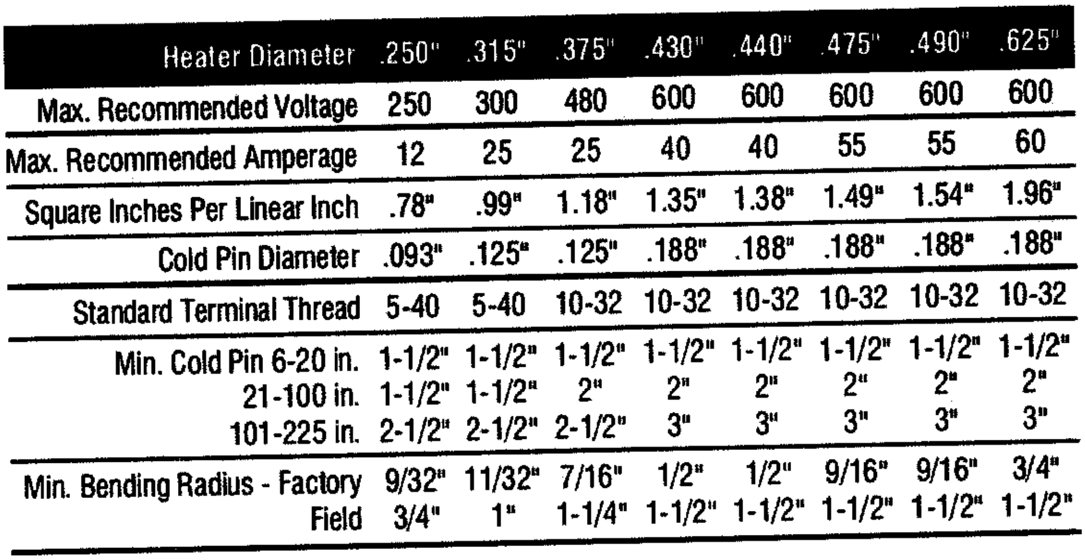
Table A8: Normal tolerances and design data for heating coil design (Heatrex, 2009)



Heater Diameter	.250"	.315"	.375"	.430"	.440"	.475"	.490"	.625"
Max. Recommended Voltage	250	300	480	600	600	600	600	600
Max. Recommended Amperage	12	25	25	40	40	55	55	60
Square Inches Per Linear Inch	.78"	.99"	1.18"	1.35"	1.38"	1.49"	1.54"	1.96"
Cold Pin Diameter	.093"	.125"	.125"	.188"	.188"	.188"	.188"	.188"
Standard Terminal Thread	5-40	5-40	10-32	10-32	10-32	10-32	10-32	10-32
Min. Cold Pin 6-20 in.	1-1/2"	1-1/2"	1-1/2"	1-1/2"	1-1/2"	1-1/2"	1-1/2"	1-1/2"
21-100 in.	1-1/2"	1-1/2"	2"	2"	2"	2"	2"	2"
101-225 in.	2-1/2"	2-1/2"	2-1/2"	3"	3"	3"	3"	3"
Min. Bending Radius - Factory	9/32"	11/32"	7/16"	1/2"	1/2"	9/16"	9/16"	3/4"
Field	3/4"	1"	1-1/4"	1-1/2"	1-1/2"	1-1/2"	1-1/2"	1-1/2"

• Diameter Tolerance	±.005 inches
• Wattage at Rated Voltage	+ 5% / -10%
• Heated Length	± 1% of overall sheath length

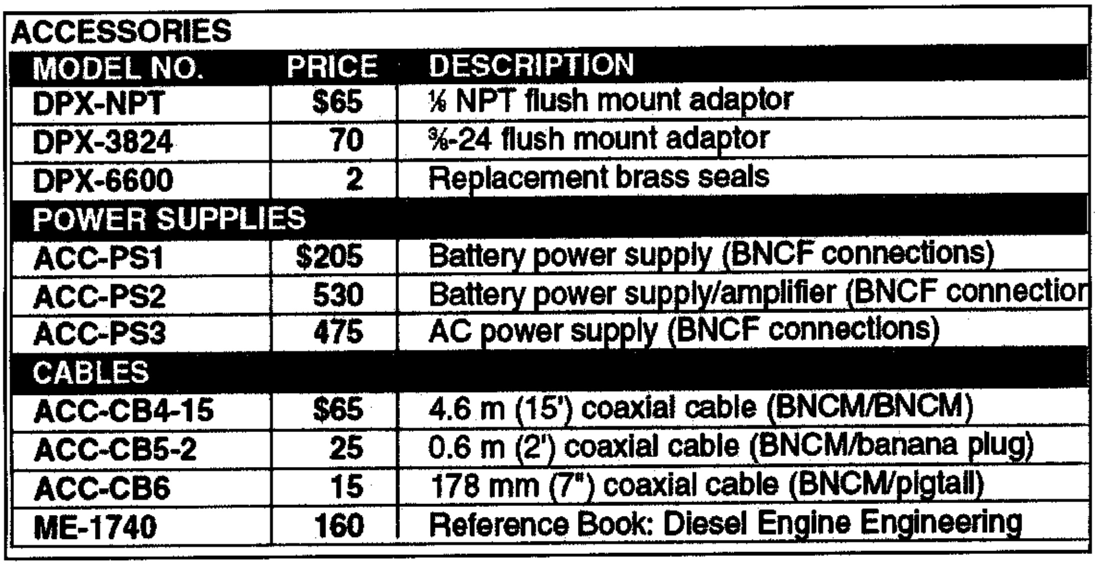
APPENDIX 14

Specification of pressure transducer for the explosion vessel

Table A8: Ranges of Pressure of Pressure Transducers (Omega, 2009)

Type	Ranges of Pressures (KPa)
DPX101-250	0 to 250
DPX101-500	0 to 500
DPX101-1K	0 to 1000
DPX101-5K	0 to 5000

Table A9: The accessories that used with pressure transducer (Omega, 2009)



ACCESSORIES

MODEL NO.	PRICE	DESCRIPTION
DPX-NPT	**$65**	**⅛ NPT flush mount adaptor**
DPX-3824	**70**	**⅜-24 flush mount adaptor**
DPX-6600	**2**	**Replacement brass seals**
POWER SUPPLIES		
ACC-PS1	**$205**	**Battery power supply (BNCF connections)**
ACC-PS2	**530**	**Battery power supply/amplifier (BNCF connectio**
ACC-PS3	**475**	**AC power supply (BNCF connections)**
CABLES		
ACC-CB4-15	**$65**	**4.6 m (15') coaxial cable (BNCM/BNCM)**
ACC-CB5-2	**25**	**0.6 m (2') coaxial cable (BNCM/banana plug)**
ACC-CB6	**15**	**178 mm (7") coaxial cable (BNCM/pigtail)**
ME-1740	**160**	**Reference Book: Diesel Engine Engineering**

APPENDIX 15

Selection of sealing material used with the lip seal for the fan

According to the DIN 3761 standards, the permissible speed for the fan according to the shaft diameter can be shown in Figure A4. The material that can withstand the highest speed in rpm is VMQ (silicone rubber) and FKM (Fluoroelastomer). However, it is found that VMQ cannot withstand the working temperature as high as FKM.

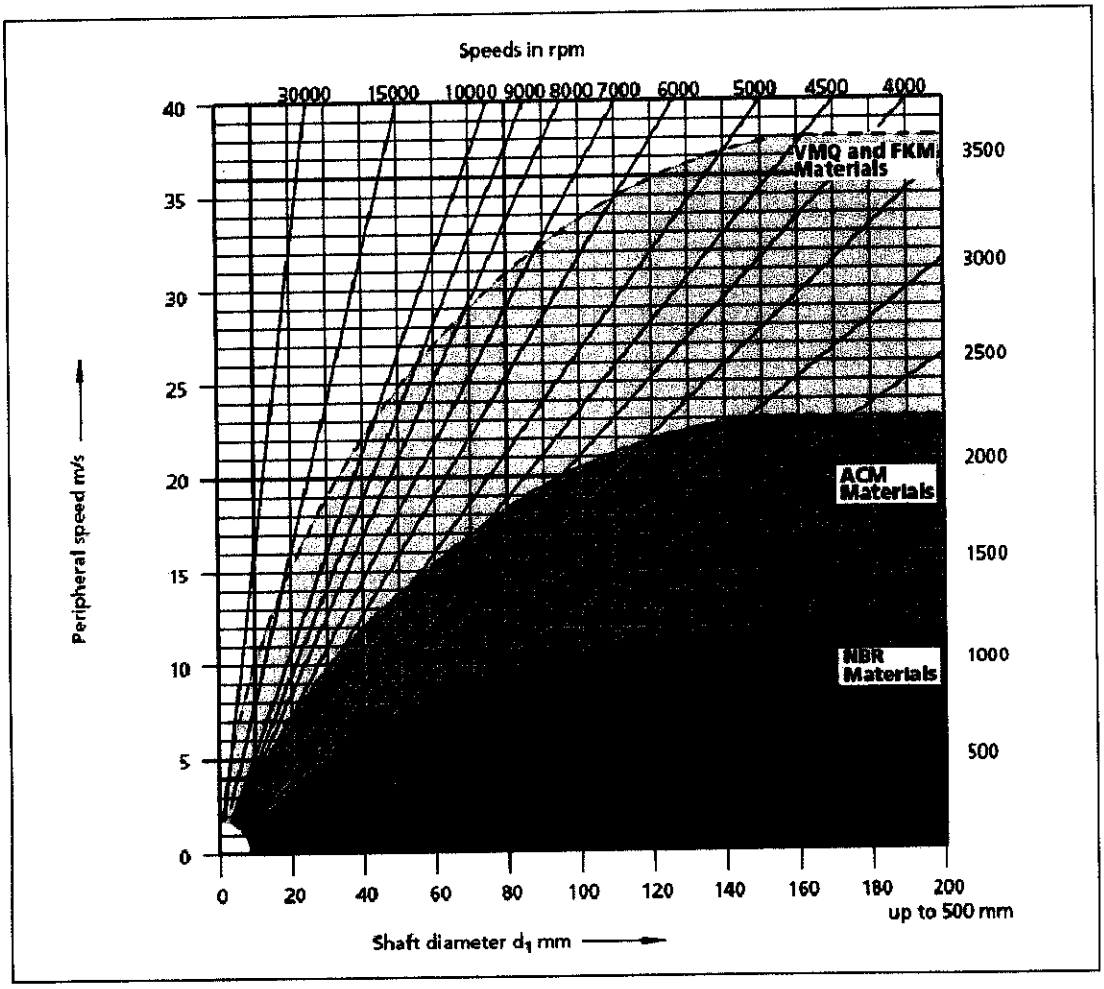


Figure A6: The permissible speeds of rotating shaft according to DIN 3761(Trelleborg, 2009)