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Preliminary Design of a Vacuum Chamber for Internal Combustion Testing Using CAE Tools and Concepts of Engineering Design

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Abstract: *The internal combustion engine finds a lot of uses in powering up various machines, especially in the automotive industry. Many performance characteristics are dependent upon the quality of combustion inside the chamber. During the recent and ongoing research and development, many tools, experimental set-ups and approaches have been developed in order to study the performance and combustion characteristics inside an internal combustion chamber. In many of these experiments, a common problem of creating pressure conditions lower than atmosphere occurs. The aim of this paper is to review concepts of engineering design and with the help of some CAE tools, present design principles of a vacuum chamber that can be used as an experimental tool to investigate the performance of internal combustion during vacuum state. The objective is fulfilled with the generation of a basic design which functions aptly for the purpose statement. This output shall be further analysed for improvement and enhancement of the design of vacuum chamber which will consequently help in determination of crucial combustion characteristics such as flame propagation, injection delay, etc. This design will serve as tool towards development of a much more detailed vacuum chamber for reliable internal combustion experimentation.*

Keywords: *Vacuum Chamber, Computer Aided Design (CAD), Computer Aided Engineering (CAE), Engineering Design Process, Finite Element Analysis (FEA).*

1. INTRODUCTION

The chamber combustion technique for powering up vehicles and other devices has become very common these days. The combustion characteristics such as flame propagation, ignition delay, duration of burn, etc. highly determine the efficiency of the engine as well as the overall performance. However the determination of combustion characteristics inside the chamber is a difficult task. Different techniques have been developed for this purpose, however in the current experimentation a common limitation of diagnosis during low atmospheric pressure or vacuum state occurs. For solving this problem a vacuum chamber is a device that can be used progressively as an experimental set-up, in order to diagnose the performance under the specified conditions. The researchers can obtain a more close-to-reality phenomenon of combustion as the low pressure or vacuum state created by the chamber provides a chance for this.

There are various standards and references available for the designing of chambers however due to the difference in need of level of research or complication, a much simpler approach is applied using the basic concepts of engineering design. The guidelines which will further be used to design the vacuum chamber are extracted from several existing research works.In terms of experimental and numerical study, Ahn et al. [1] have discussed the combustion characteristics of oxy fuel burner. Petrovic [2] have investigated on the influence of forces which act on a nozzle of a pressure vessel by utilizing finite element method.

The current design review is aimed at presenting a primary design results of a simple but functional vacuum chamber, which is able to withstand generally applied internal pressure in most common applications. This pressure numerically is about 15MPa.

It might be possible that the final design result might be similar to some other currently present chambers in the industry however it is a preliminary design and it will serve as a tool and an experimental set-up for further research into the flow and combustion diagnostics field. This chamber will be used in the determination of ignition characteristics of different liquid fuels under varying pressure and temperature.

An important factor in the performance of the vacuum chamber is the material selection process and for this a comparison in terms of Von-mises stress has been carried out using various computer aided engineering tools for simulation.

2. DESIGN PROCESS

For basic guidelines required for the design process several types of manuals and references have been studied [3-6]. The design must also comply with the ASME Boiler and Pressure Vessel Code 1992 and also with ANSI Standards B36 and B16. The methodology for generating this design can be broken into 3 phases: Theoretical Analysis Phase; Primary Design Analysis Phase; Result Architecture Analysis Phase.

2.1 THEORETICAL ANALYSIS PHASE

An important aspect in product design is the defining of the various pre requisites of the usage.An internal pressure of 15MPa was decided to be the maximum pressure sustainable inside the vacuum chamber. Keeping this requirement in mind, the basic design, materials, size, shape and other specifications were chosen on the basis of engineering design concepts and the available options are analyzed.

Theoretically, for finding out the safety factor of the product, the Failure Theories concept shall be used. One of the most common theories which can be used is the Von Mises criterion; which states that failure occurs when the energy of distortion reaches the same energy for yield in uniaxial tension [7]. In order to ensure that the product will not yield during operation, the Von Mises stress value must be smaller than the yield stress of thematerial. The safety factor of the product is targeted within N = 1.5 ~ 4. Other than that, the basic equation related to Thin-Pressure Vessel design shall be referred as basis for the pressure vessel calculation. The used equations are as follows:

$$\sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}} \leq \sigma_y$$

σ_y = Yield Stress
σ_1, σ_2 , σ_3 = Principal Stress

$$\sigma_l = \frac{pr}{2t} \qquad \sigma_h = \frac{pr}{t}$$

σ_l = Longitudinal Stress
σ_h = Hoop Stress
p = Pressure
r = Radial
t = Thickness

2.2 PRIMARY DESIGN ANALYSIS PHASE

For designing a low cost yet reliable vacuum chamber, specific conditions such as deflection control, best materials selection, proper surface preparations, design of the structural components, engineering the heating, cooling, shielding system, mechanism and several other criteria, should be controlled on in order to designing a good vacuum chamber.

The design of a vacuum chamber can be found in almost any shape and size imaginable for example, sphere ellipsoid, cylinder with domed ends, cone, geodesic ball (triacontrahedron), diamond (octahedron), cylinder with flat ends, pyramid (tetrahedron) and box [5].

Another important aspect during the configuration design phase is the material selection process. During this stage, the property of materials must be analysed in order to meet the design requirement. For the head, shell and flange, the materials must have good forming and welding properties which is important properties because forming and welding are the important process in fabricating a chamber. Next, the material must have good corrosion and oxidation resistant and ease of cleaning, fabrication and beauty of appearance which will ease the maintaining process of the chamber. Finally, the material for the optical window must have excellent optical quality, very low thermal expansion, and exceptional transmittance over a wide spectral range, especially in the ultraviolet. It must also have good resistant to scratching and thermal shock [8].

The shape of the chamber can affect its volume and surface area. The smaller the total surface area, the smaller the quantity of gas loads from desorbing water molecule. Indirectly, this can reduce the pumping time of the chamber [9]. By choosing the right shape, the surface area can be reduced. Rectangular chamber are generally more expensive than other configuration. However, rectangular chamber is one of the preferred choice because on the ease of accessibility or when large chamber mass is required vibration dampening. Other than that sphere shape chamber is known to be less expensive and has less internal volume.

3. RESULTS AND DISCUSSION

Various options for the structural shape and architecture of the device have been evaluated. The options for the main body included cylindrical, spherical and box shaped design. A hemisphere, ellipsoid or no head design was taken into consideration in case of head design. After the conceptual analysis stage, cylindrical shaped vessel was chosen as the main body and hemispherical shaped head was chosen as the cover. By working on the concept and idea developed in the preliminary design phase, the final shape of chamber was developed.For the ease of analysis and further improvement, the vacuum chamber design was divided into four main modules which are the Main Body (cylindrical shell), hemispherical head (cover), the Window Flange and the Optical window. The design of the chamber was developed using the design software SolidWorks and the different views of the configurational model are given in figure1.

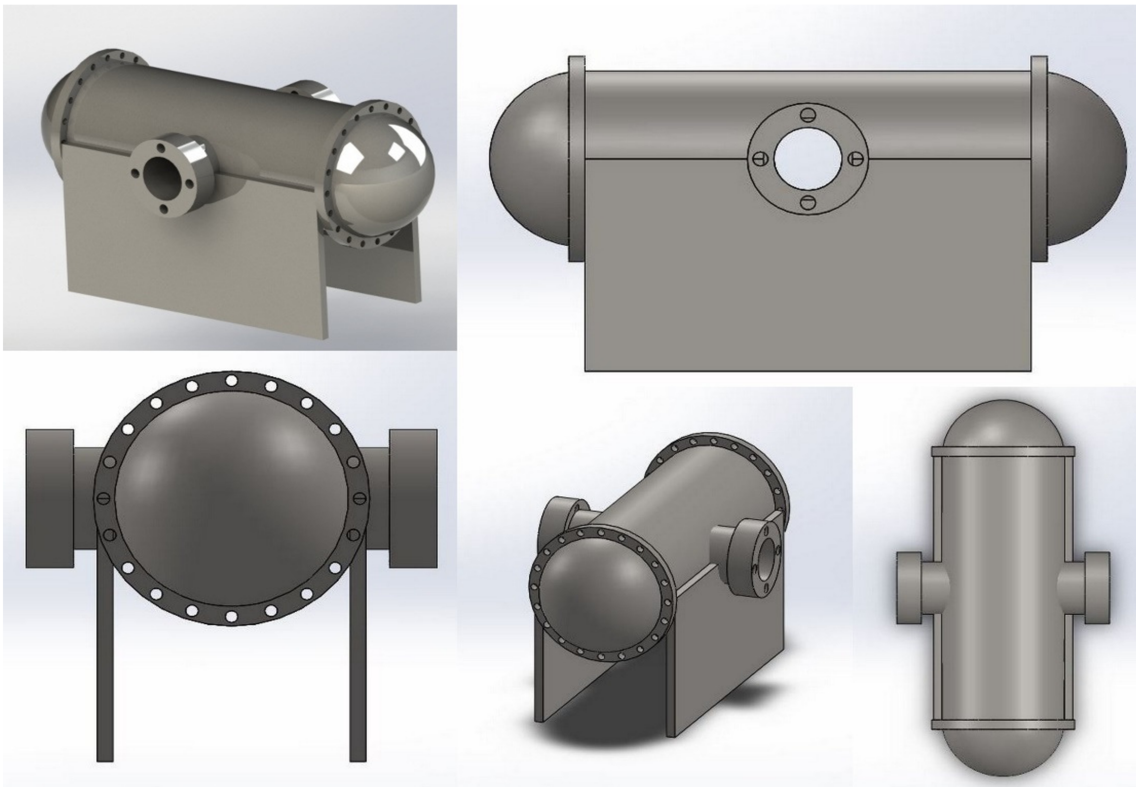

Fig. 1. Different views of the Chamber Model

Now, for the analysis of the generated design, the chamber is subjected to several constraints. Also, the parameters of the product are controlled using this analysis.

The following constraints were taken into consideration.

1. Maximum stress must not exceed the yield strength of the chamber's material. This will ensure that there is no plasticity during the running state of chamber.
2. The chamber must have a minimum internal volume of 60 litres. This will ensure that the chamber will have sufficient volume for experimentation activities.
3. the outer diameter must be less 0.5 m and the overall length of vessel must be less than 1.0 m. Smaller chamber size contributes to easier access on transport and will consumed lesser space compared to normal conditions.
4. The overall thickness must be less than 10% of the radius. This constraint has been introduced so that the chamber could satisfy thin-walled pressure vessels characteristics.
5. The total elongation of the vessel should not exceed 1.0 mm

CAE tools were used keeping in mind all the variables and constraints and the optimum size for this vacuum chamber was computed. The formulae were programmed using MATLAB and as a result the optimum size of the chamber was calculated. For the ease of designing, analysis and understanding the final dimensions were taken as follows: (Table 1).

TABLE 1: Chamber parameters

Parameter	Calculated Result (mm)	Final Dimensions (mm)
Outer Radius (Main body)	148.2	150
Length (Main Body)	706.8	700
General thickness	14	15

4. MATERIAL SELECTION AND COMPARATIVE ANALYSIS

The material selected for construction of chamber should have good forming and welding properties, which is an important process in fabricating the chamber. In terms of material properties, the material should have good corrosion and oxidation resistance, ease of cleaning and fabrication, and finally good appearances, which will ease the maintenance process of the chamber. Also, considering the factor of design for human, the selection of a user friendly material is necessary especially in maintaining the cleanliness of the chamber [9].

Firstly SUS304 Stainless Steel was considered for the main body material, because of the common use in tanks and vessels design. Also mild steel is a material that can be considered and it has also been evaluated.Based on literature studies, SUS304 Stainless Steel is had been chosen as the primary material for metal component.

TABLE 2: Comparative analysis for the material selection process

Part name	Material type	Yield Strength	Density	Modulus of Elasticity
Hemisphere Head	304 SS	290 MPa	8030 Kg/m^3	193 GPa
	MS	248.17 MPa	7800 kg/m^3	200 GPa
Main Body	304 SS	290 MPa	8030 Kg/m^3	193 GPa
	MS	248.17 MPa	7800 kg/m^3	200 GPa
Window Flange	304 SS	290 MPa	8030 Kg/m^3	193 GPa
	MS	248.17 MPa	7800 kg/m^3	200 GPa
Optical Window	Fused Silica	60 MPa	2203 Kg/m^3	73 GPa
	Borosilicate Glass	67 MPa	2230 kg/m^3	74 GPa

Next, fused silica has been chosen for the optically flat window material because of the excellent optical quality, very low thermal expansion, and exceptional transmittance over a wide spectral range, especially in the ultraviolet. It also has good resistant to scratching and thermal shock. Borosil glass was also considered as an option for the window material. The comparative analysis for the material selection process is given in table2.

Using the final parameter as base, the 3D shape has been generated using SolidWorks software (Fig. 1). Next, the Finite Element Analysis (FEA)has been applied using the simulation software ANSYS (Fig. 3). The result shall be discussed in the nextsegment.

5. CONCLUSIONS

1. Von-Mises criteria was considered first to obtain the maximum distortion energy value of the chamber and the elongation of the chamber due to the design pressure. Considering the yield stress of SUS304 Stainless Steel material which is around 290 MPa; based on calculation, the safety factor for the most critical area on the main body is approximated around n=1.113 (Figure 2(i)). The analysis result is 3.7 times lower compared to the manual calculation of the main body which is around n=4.12. Further studies need to be done to reinforce the openings section, to reduce the stress concentration on the critical areas. Even though the result is safe ($n > 1.0$) and majority of the main body is within good range ($n \approx 2$), it is best if we could push the safety factor of the critical region within the optimum range, which is within n=1.5 ~ 4. As a simple solution, by increasing the thickness from 15 mm to 25 mm, this result can easily be achieved. Another type of improvement that can be done is by increasing the welding height of the joints area.
2. In case of the Hemisphere Head (Figure 2(ii)), a good result was achieved which is around n = 3.9. Even though the safety factor is smaller compare to the theoretical calculation which is n = 6.7, the result is good and within optimum range.
3. For the next analysis, based on theoretical calculation, the elongation of the chamber is around 0.155 mm. In theory, the chamber's design is able to satisfy the requirement which is the elongation constraint must be less than 1.0 mm. Compared to the simulation output, the actual result is slightly higher which is around 0.243 mm. However, this is still below the specified requirement, so this design can be considered as safe.

As a conclusion, the main objective which is to come out with a preliminary design of a functional and optimum weight vacuum chamber was achieved. Listed below are the overall summary of the design review output:Based on theoretical analysis and simulation result, the chamber is able to withstand the design pressure of 15 MPa.The optimum weight of the chamber been achieved which is around 1078 N or 110 kg.

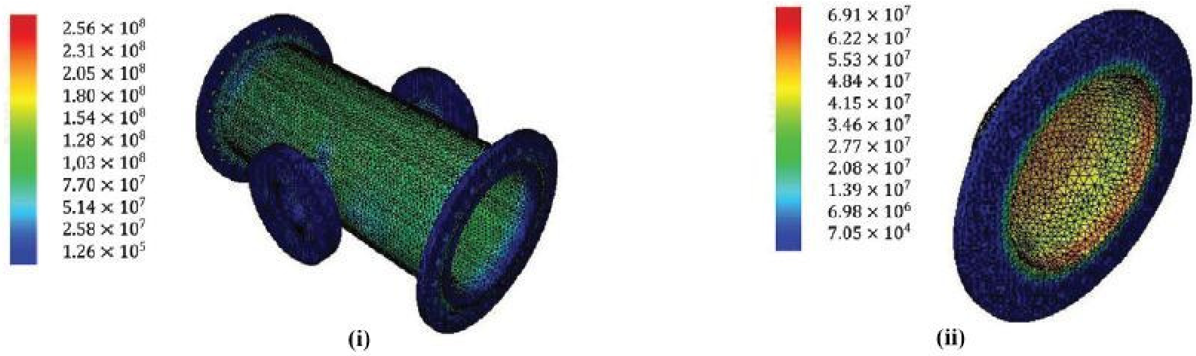

Fig. 2. Computer Aided Analysis of the main body and the hemispherical head

6. FUTURE RESEARCH

The chamber so developed can be further used as an apparatus for determining combustion properties of different fuels and even the combustion characteristics of many real thermodynamic processes. The further research done on this chamber includes determination of ignition characteristics of different liquid fuels generating direct injection engine conditions.

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