DESIGN OF A CONSTANT VOLUME COMBUSTION CHAMBER WITH OPTICAL APPROACH TECHNIQUE

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Abstract. The combustion process in the internal combustion engine is realized as the core of the engine's power and exhaust emission formation. This paper describes the design of a constant volume combustion chamber (CVCC) to simulate the combustion process of the diesel engine with the optical approach technique. The technical design standards of the chamber were based on the actual conditions of diesel engines with a compression ratio of 16 to 28 and an injection profile with a fuel pressure varying between 400 and 1600 bar. The system included 2 quartz crystal windows that allow observing the entire process of fuel injection and combustion taking place inside the chamber. The structural strength analysis of the design under simulating pressure was carried out by ANSYS software. The results revealed that the chamber met durable standards with each type of material based on design criteria with a pressure of 200 bar selected as the ambient pressure inside the chamber.
Keywords. Constant volume combustion chamber, diesel engine, combustion characteristics, high injection pressure system, optical approach technique.

1. INTRODUCTION

Diesel engines have higher thermal efficiency than gasoline engines, although exhaust pollution is always a concern in diesel applications. Increasingly stringent environmental regulations are driving research into diesel engine technology. Several scientific solutions have been applied worldwide to reduce pollution, improve efficiency, and decrease the dependence on fossil fuels [1]-[5]. Improving the processes that directly affect fuel combustion efficiency is an important issue in this context. In addition, when optimizing the influence of alternative fuel properties, it was found that the use of these fuel sources minimizes emissions that are hazardous to health [8],[9]. NO_x emissions are also reduced by using exhaust gas recirculation technology [5],[10]. To investigate the above impacts, diesel engines have been studied and evaluated using several systems, including engine dynamometers, remote emission measurement systems, and others. These systems have helped to study the effects of different fuel types on engine performance and emission characteristics. On the other hand, an in-depth study aims to provide the most direct results about the combustion process, and the selected optical chamber systems offer greater benefits.

Various optical systems have been used, including optical research machines, rapid compression and expansion machines, and constant volume combustion chambers (CVCC). The advantages and limitations of each type of device were summarized by Rik Baert, et al. [11] and Oren, et al. [12]. Due to the simplicity of design and operation, the CVCC system has become a potential tool for fuel combustion process research. CVCC allows the simulation of various experimental settings to explore the spray development and combustion process. The CVCC system also provides valuable parameters for studying and understanding the complex mechanism of diesel fuel injection and combustion under actual diesel engine operating conditions. The chamber with modern optical methods is a very useful tool for accurate observation of the fuel injection and combustion process by combining of high-speed camera [13]. The CVCC system has been used in work by J. Zhang, et al. [5], S. Marasri, et al. [6], C. Xu, et al. [7], Rik Baert, et al. [11],…

This research focuses on using an optical approach based on the schlieren technique to design CVCC devices. With the preliminary design of CVCC and the ability to be fabricated, CVCC will be used to evaluate the impact of abundant biofuel sources applied in Vietnam as renewable fuels to reduce dependence on fossil fuels [14][15][16][17].

2. RESEARCH METHODOLOGY

2.1. Optical technique in Schlieren

Schlieren optics come in a variety of configurations, including single-lens systems, dual-lens systems, and Z-mirror systems. The Z-shaped mirror system in Fig. 1 is commonly used in CVCC systems to study the combustion process [7],[18],[19]. The light from the lamp enters through the pinhole and serves as the light source. A parallel beam of light emanates from the spherical mirror M1. Due to the density difference, the parallel light rays passing through the object under observation are deflected. The light beam is focused by a spherical mirror M2 on the opposite side of the area to be examined. Depending on the test case, a knife-edge or pinhole is used to partially block the light rays. The rear is placed on a high-speed camera to obtain an image of the change in light intensity due to the deflection of the light rays as they pass through the area of interest. For non-reacting sprays, a pinhole is used to obtain a dark spray on a bright image background. For reacting sprays, the knife-edge is used to obtain a bright spray on a dark image background.

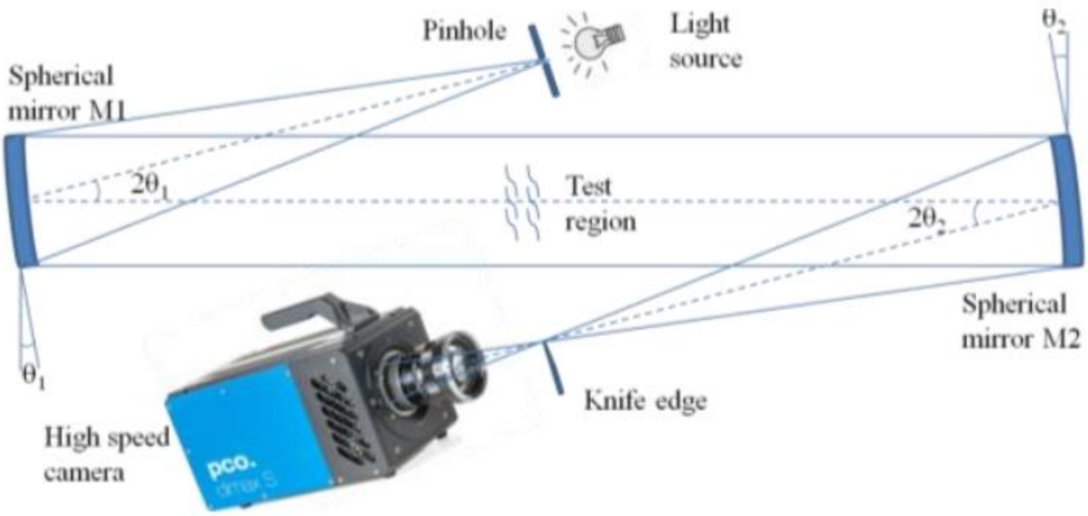

Figure 1: Optical system design Schlieren imaging of the Z-shaped mirror system [20]

2.2. Simulation of diesel engine combustion conditions

Fig. 2 shows the two steps of a CVCC simulation of diesel engine combustion conditions: the combustion environment generation and the diesel fuel combustion. In step 1, a gas mixture of acetylene (C_2H_2), oxygen (O_2), and nitrogen (N_2) is introduced into the chamber and ignited by the spark plug. Premixed combustion releases high temperature and pressure. Since the peak pressure in step 1 is high compared to actual diesel engine conditions, the mixture takes a short time to transfer heat through the chamber wall and cool down, resulting in a pressure drop. In step 2, when the pressure has dropped to the desired pressure by the detection of a transducer pressure sensor, the ambient conditions in the chamber resemble those of the diesel engine. The high-pressure diesel fuel is injected into the interior of the chamber, and the fuel begins to burn.

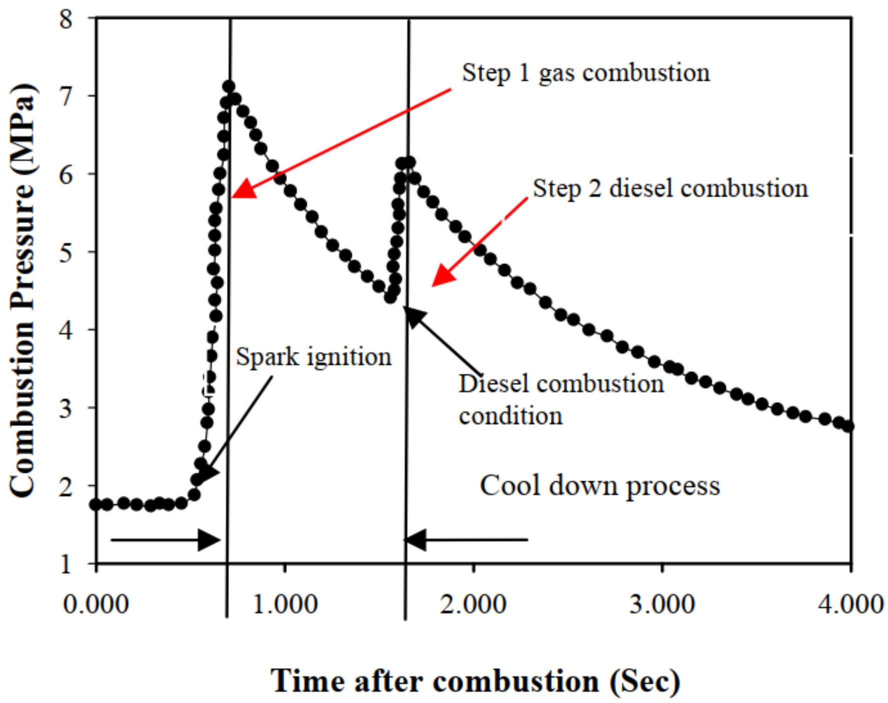

Figure 2: Pressure developments in the CVCC [21]

3. COMBUSTION CHAMBER DESIGN

3.1. Design standards:

To simulate the ambient air conditions at the top dead center (TDC) of the diesel engine, the design standard of the chamber must include the pressure and temperature values of the diesel engine with the usual range of compression ratios (from 16 to 28). Fig. 3 and Fig. 4 show the effects of compression ratio and polytropic index (n) on ambient air conditions. Ambient air pressure, temperature, and density increase as the compression ratio increases. The thermal compression exponent interrupts the pressure increase and the temperature increases with time. Pressure, temperature, and air density at TDC range from 36-106 bar, 685-1130 K, and 18-34 kg/m^3 at a compression ratio of 16-28.

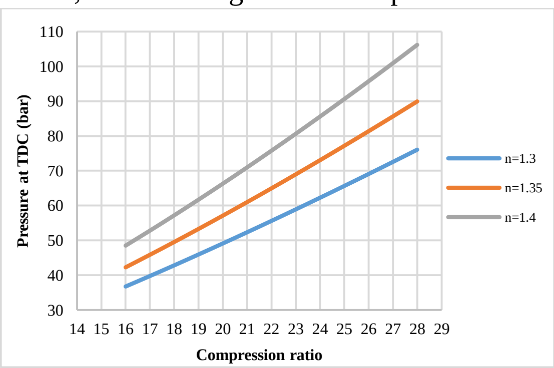

Figure 3: Relationship between pressure at TDC and compression ratio with various polytropic index (n)

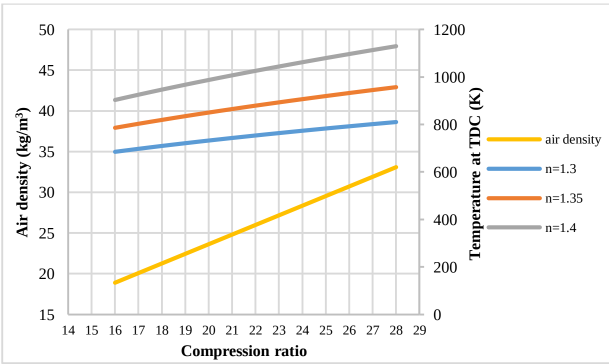

Figure 4: Relationship between the temperature at TDC, air density, and compression ratio

Normally, the size of the diameter of the chamber is influenced by the spraying process and the combustion process. If the inner diameter of CVCC is too large, the increase of combustion pressure process is too slow; On the other hand, the smaller of inner diameter may cause the spray impingment on wall, so the analysis of the spray development and combustion pressure in the CVCC becomes difficult [22]. Therefore, it is necessary to determine the size of the chamber. The comparison shows that most of CVCC in many kinds of research have the same diameter from 80mm to over 100 mm.

Table 1: CVCC geometry in the using pre-combustion technique

No.	Authors	Area of interest	Fuels	Chamber geometry	
				Diameter (mm)	**Width (mm)**
1	Baert et al. [11]	Fuel Injection and Combustion	D	100	N/A
2	Oren et al. [12]	Combustion of fuel	D	101.6	44.5
3	Fujimoto et al. [23]	Flue gas characteristics	D	70	26
4	J. Zhang and T. Fang [24]	Combustion of fuel	D	101.6	25.4
5	Nguyen Ngoc Dung [25]	Combustion of fuel	H_2, NG, BD	80	30
6	R. Munsin [26]	Combustion of fuel	E	100	45
7	Yilu Lin et al. [27]	Combustion of fuel	ABE/D	110	N/A
8	Sieber et al. [28]	Ignition and combustion of fuel	D/E	80	29
9	Nguyen et al. [29]	Ignition	H_2, NG	80	30

**Note:* *A = Acetone, B = Butanol, BG = Biogas, D = Diesel, E = Ethanol, Ad = Additive, ME = Methanol, BD = Biodiesel,* H_2 *= Hydrogen and NG = Natural Gas*

3.2. Simulation conditions

Table 2 and table 3 list the parameters of the materials used in this design and simulated objects. For the chamber body, internal quartz holding block, and external quartz holding block, stainless steel 304 is chosen because of its high strength and anti-corrosion. For the optical window, synthetic quartz is chosen because it has very high strength, wide range of light transmission, and stable operation at high operating temperatures up to 1573 K. Table 4 summarizes the conditions for the CVCC durability simulation. In the simulation, a pressure of 200 bar is chosen as the load.

Table 2: Material specifications

Components Control	Unit	Materials	
		Stainless steel 304	**Synthetic quartz**
Density	kg /m^3	7750	2200
Young's modulus	GPa	193	74
Poisson's ratio		0.31	0.17
Tensile strength	MPa	586	500
Compressive strength	MPa	207	1130

Table 3: Simulated objects

Simulation Objects	Materials
Chamber body	Stainless steel 304
Internal quartz holding block	Stainless steel 304
External quartz holding block	Stainless steel 304
Optical window	Synthetic Quartz

Table 4: Simulation parameters of measuring chamber durability

Parameters	Unit	Value
Testing Pressure	bar	200
Temp. chamber body	K	600
Optical window temperature	K	400

4. RESULTS AND DISCUSSION

4.1. 3D Design of a Constant Volume Combustion Chamber

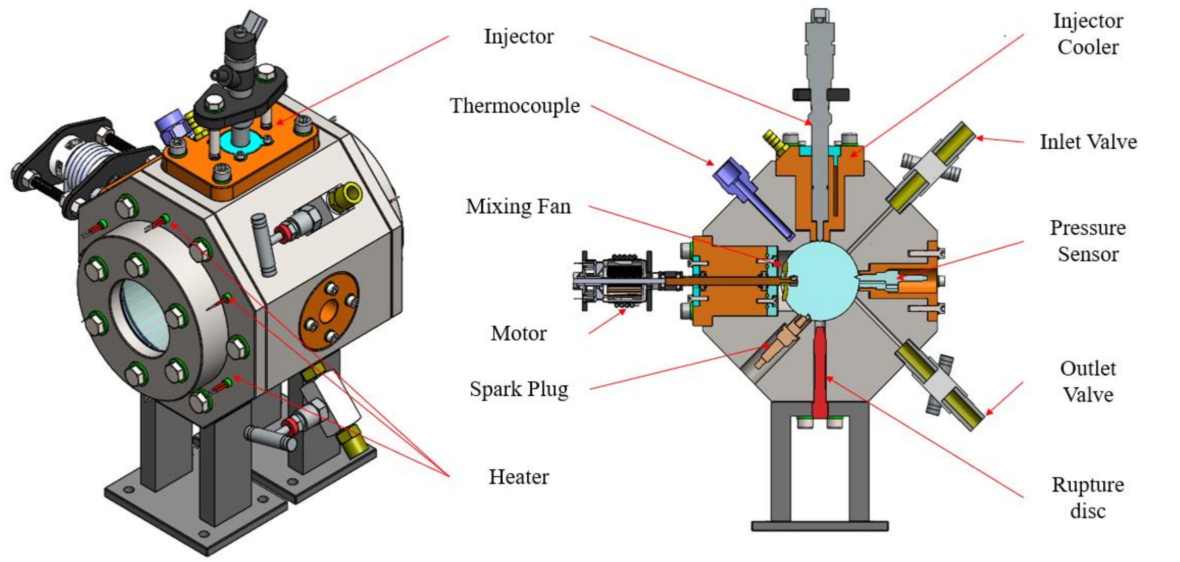

Figure 5: General arrangement of equipment in the chamber

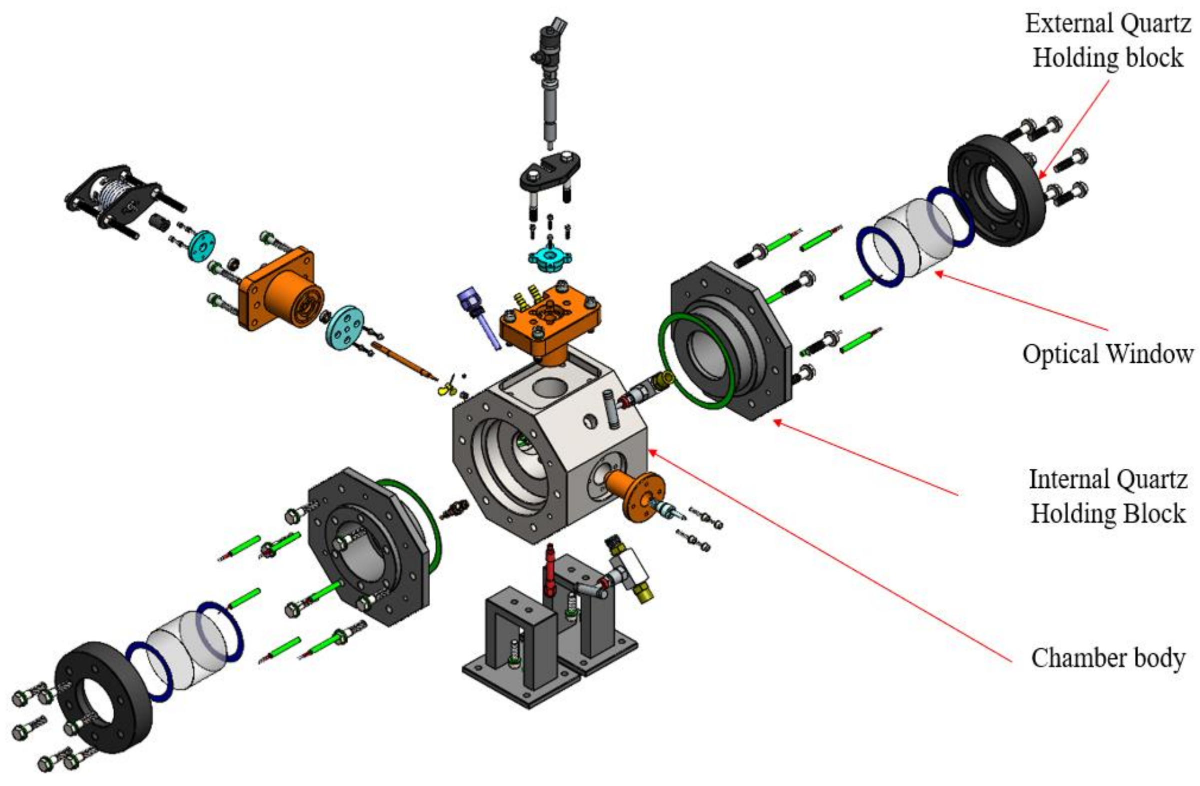

Figure 6: View of the decomposition of the CVCC geometry.

Fig. 5 and Fig. 6 show the shape and arrangement of the individual parts of the chamber. The geometry inside the chamber has a cylindrical profile with a diameter of 80 mm. To facilitate the installation of the surrounding equipment, the internal width of the chamber is 102 mm. The two optical windows are made of quartz glass with a total diameter of 100 mm and a thickness of 70 mm. The injector is installed above the chamber and is fixed by an injector holder. The cooling water piping system is integrated into the injector holder to prevent the nozzle from being damaged due to the characteristics of the CVCC system with high operating temperatures. The mixing impeller mounted in the chamber has a diameter of 44 mm and is driven by an electric motor DC with a speed of approximately 4000 rpm. To avoid the condensation of steam on the optical window, the heating system of the chamber includes 12 heating elements and a temperature sensor mounted on the body of the chamber. The temperature of the chamber wall normally keeps the line stable at 400 K. This value was chosen because it is high enough to prevent evaporation the amount of condensate is also small enough to facilitate the cleaning of the chamber after the test [11]. To ensure safety, a rupture disc serving as a safety valve with a pressure limit of 170 bar was installed in the chamber to reduce the risk of accidents as well as damage to components mounted on the chamber body (pressure sensors, nozzles, etc.) if the pressure rises too high.

4.2. Results of the analysis

The results of the simulation show that stresses and deformations occur in different parts of the CVCC when the pressure in the chamber reaches 200 bar.

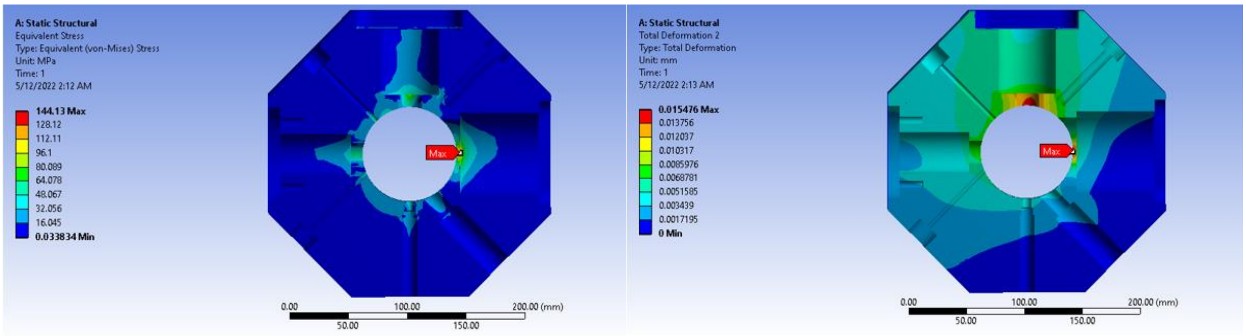

Figure 7: Distribution of stresses and deformations in the chamber body

Fig. 7 is the result of the strength of the chamber body. The maximum stress at the point of installation of the air-conditioning impeller is 144.13 MPa, which is less than the allowable stress of 207 MPa with a safety factor of 1.4362. The largest deformation in the positions of the nozzle and the air mixing unit is 0.015476 mm.

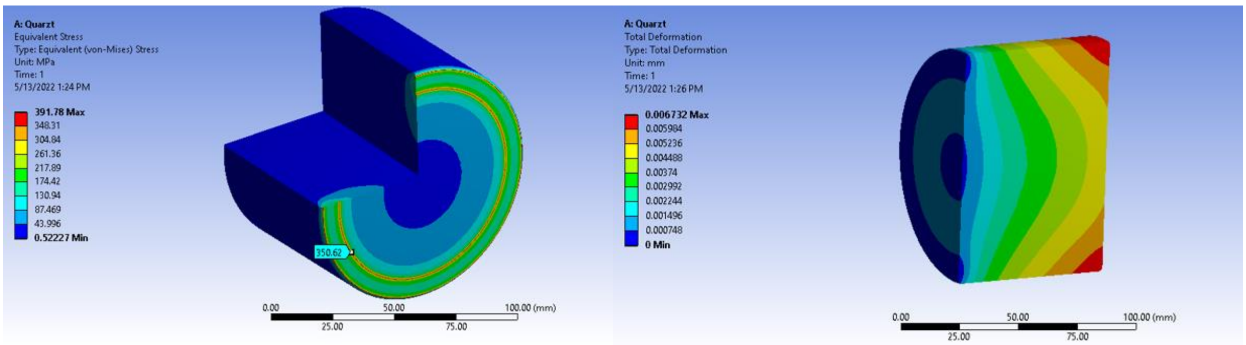

Figure 8: Distribution of stresses and deformations in quartz window

Optical window toughness results are shown in Fig. 8. The maximum stress at the point of contact with the external quartz retaining block is 391.78 MPa, which is less than the allowable stress of 1130 MPa with a safety factor of 2.86. The largest deformation at the side in contact with the chamber is 0.006732 mm.

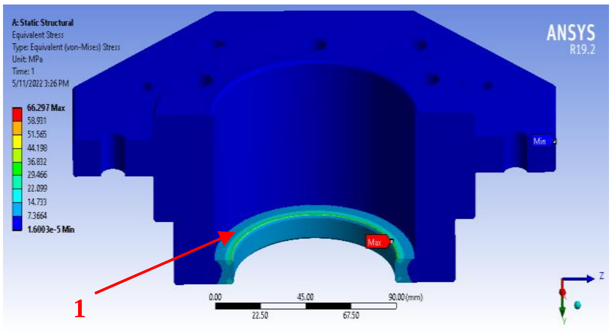

Figure 9: Stress distribution in the internal quartz holding block

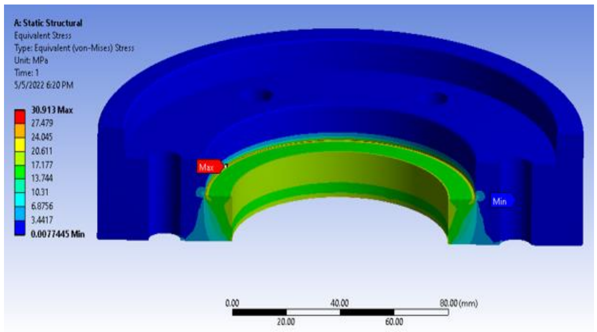

Figure 10: Stress distribution in the external quartz holding block

Fig. 9 and Fig. 10 are the results of stress distribution on the external quartz retaining block and the internal quartz retaining block. Fig. 9 shows the location of the extreme stress of the internal quartz holding block in the contact area of the optical window at the marked location 1. The maximum stress value is 66.297 MPa with a safety factor of 3.122. Fig. 10 shows that the maximum stress after simulation of the external quartz holding block is 30.913 MPa at the quartz window contact point and is exerted by the quartz block with a safety factor of 6.696.

5. CONCLUSION

This paper describes the geometry and profile of chamber and optical windows, an overview of the operating principles, and details of the equipment used in CVCC.

The CVCC can be fabricated and tested after the required durability has been demonstrated by durability analysis using simulation software. From the results of the durability analysis of the combustor under the simulated pressure condition of 200 bar, it is evident that it is possible to meet the operating conditions of the CVCC under simulated diesel conditions such as various compression ratios up to 28with the selected design option.

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THIẾT KẾ BUỒNG CHÁY ĐẲNG TÍCH VỚI KỸ THUẬT TIẾP CẬN QUANG HỌC

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Tóm tắt: Quá trình cháy là cốt lõi trong sự hình thành công suất và khí thải của động cơ. Bài báo này mô tả thiết kế buồng cháy đẳng tích để mô phỏng quá trình cháy của động cơ diesel với kỹ thuật tiếp cận quang học. Các tiêu chuẩn thiết kế kỹ thuật của buồng cháy được xây dựng dựa trên các điều kiện thực tế của động cơ diesel với tỉ số nén từ 16 đến 28 và biên dạng tia phun với áp suất nhiên liệu thay đổi trong khoảng từ 400 đến 1600 bar. Hệ thống bao gồm 2 cửa sổ bằng tinh thể thạch anh cho phép quan sát toàn bộ diễn biến quá trình phun và đốt cháy nhiên liệu diễn ra bên trong buồng cháy. Kết cấu của thiết kế được phân tích bền bằng phần mềm ANSYS. Kết quả mô phỏng cho thấy buồng cháy đảm bảo tiêu chuẩn bền với áp suất 200 bar được lựa chọn làm áp suất tác động bên trong buồng cháy.

Từ khóa: Buồng cháy đẳng tích, động cơ diesel, hệ thống phun áp suất cao, đặc tính tia phun, kỹ thuật tiếp cận quang học.

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