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DEVELOPMENT OF A CONTROL-INDICATING SYSTEM FOR THE CONSTANT VOLUME COMBUSTION CHAMBER

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Abstract: Researching the optimization of the combustion process using the Constant Volume Combustion Chamber (CVCC) system is one of the effective methods for investigating the influencing factors on the combustion process and the formation of exhaust gases from the fuel utilized in internal combustion engines. This research focuses on developing control algorithms for the CVCC system based on synchronized signals from spark plugs, dynamic pressure sensors, fuel injectors, and real-time data logging to adjust the air-fuel mixture ratio (C_2H_2, N_2, O_2) in order to create operating conditions similar to the late compression stage in diesel engines and simulate exhaust gas recirculation. The three oxygen concentrations after premixed combustion (ignition) of 21%, 15%, and 10% were selected for experimentation in the CVCC system before the diesel fuel injection phase begins at an initial mixture pressure of 14 bar. The results indicate that the system has effectively controlled and recorded data with a high level of accuracy, an observed deviation of 2.24% was found when analyzing the values of maximum combustion pressure after ignition at the experimental oxygen concentrations. Additionally, the electronic systems fully adhere to the trigger signals and the calculated time control signals to determine the air-fuel ratio accurately.

Keywords: Constant volume combustion chamber (CVCC), Common rail system (CRS), Data acquisition and control system (DAC), Diesel engine.

1 INTRODUCTION

The emissions from diesel engines and the increasingly stringent emission standards pose significant challenges to the widespread application of this engine type across various sectors. The integration of electronic fuel injection technology (common rail) and the use of biofuels aims to optimize combustion process efficiency and diversify energy sources in engines, offering a potential solution to reduce environmental pollution and address the global energy crisis [1]. Numerous researchers have dedicated their efforts to exploring diverse avenues within this solution. M. Lapuerta et al. [2] investigated autoignition in a constant volume combustion chamber using a blended fuel mixture of n-butanol and ethanol with either diesel or biodiesel fuel. They concluded that the application of biofuels led to a reduction in autoignition delay time with an increase in the initial temperature of the combustion chamber, while the delay time increased exponentially with a decrease in the initial pressure of the combustion chamber. The study conducted by S. Godiganur et al. [3] investigated the performance and emissions of fish oil, and the results indicated that biodiesel B20 exhibits higher thermal efficiency compared to diesel fuel, along with a notable reduction in NO_x emissions ranging from 3% to 21%. J. Zhang, et al. [4] employed the two-color method to analyze the combustion process of diesel and biodiesel through impact of soot temperature and KL factor. The research indicated that biodiesel tended to generate less soot and a lower KL coefficient (10%) during combustion. H. Liu et al. [5] carried out research and concluded that E20S80 exhibited several advantages in terms of soot emissions when compared to B20S80. Furthermore, additional studies on heat transfer in isovolumic combustion chambers have been conducted by Oppenheim and Kuhl [6]. More recently, M. Lapuerta, et al. [7] and J. Hwang, et al. [8] utilized a constant combustion chamber to investigate microwave-assisted plasma ignition. Their research concluded that flame speed increased by up to 20% during microwave-assisted plasma ignition.

In the aforementioned studies, the Constant Volume Combustion Chamber (CVCC) has been employed to delve into diverse facets of combustion characteristics. These investigations encompass exploring the impact of flame temperature on soot formation within the combustion chamber, examining novel fuel types, and scrutinizing the effects of spray nozzle shape on the combustion process among other factors [9]-[12]. However, the predominant focus in current studies is on utilizing the constant volume combustion chamber to examine factors influencing combustion efficiency. Overall, there is a paucity of research dedicated to elucidating the foundational principles of combustion chamber development. H. Alireza et al. [13] presented the design of a combustion chamber with a maximum pressure of 100 bar for researching a direct injection SI-CNG engine. Meanwhile, R. Munsin et al. [14] designed a combustion chamber to simulate a CI engine and concluded that the diameter and height of the cylindrical combustion chamber must be equal to or greater than 100mm and 25mm, respectively. However, the rationale for conducting research on optimizing the control process has not yet been clearly demonstrated. This research focuses on developing control algorithms for the constant volume combustion chamber system based on synchronized signals from the spark plug, piezo transducer pressure sensor, fuel solenoid injector, and real-time data logging to adjust the combustible gas mixture ratio (C_2H_2, N_2, O_2) in order to create operating conditions similar to the late compression phase in a diesel engine and simulate the exhaust gas recirculation.

2 MATERIAL AND METHODS

2.1 The Method of Pre-combustion Technique

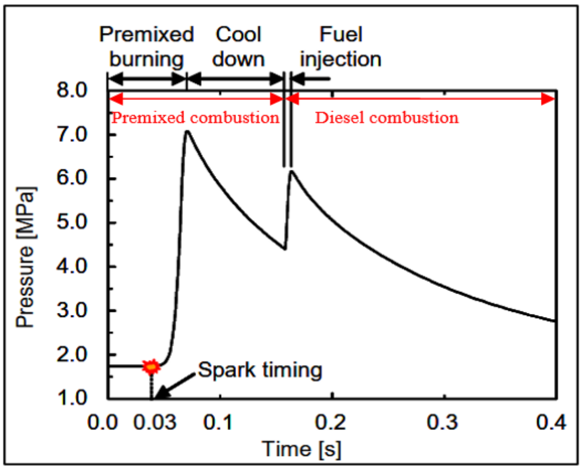


Figure 1: Graph of the combustion pressure variation inside the CVCC system [17].

Figure 1 illustrates the pressure variation inside the CVCC during a test cycle. This combustion process is divided into two stages: the premixed combustion stage and the diesel combustion stage. In the premixed combustion stage, a mixture of Acetylene (C_2H_2), Nitrogen (N_2), and Oxygen (O_2) gases is charged into the constant volume combustion chamber in the predetermined calculated proportions. Subsequently, the mixing fan is activated to homogenize the freshly loaded gas mixture for combustion. Finally, the spark plug ignites the homogenized gas mixture generating high pressure and temperature inside the combustion chamber. The pressure rises to its initial peak and then gradually decreases due to heat transfer through the walls of the combustion chamber until it reaches the desired temperature and pressure conditions, similar to the compression conditions of a diesel engine. Following, fuel is injected into the combustion chamber, initiating the diesel combustion process, resulting in an increase in pressure within the chamber and reaching its second peak. The pressure variations during the combustion process in the combustion chamber are recorded and analyzed.

The temperature following the initial phase can be computed by utilizing recorded pressure signals and certain assumptions. These assumptions encompass the consideration of the combustion process of the premixed fuel and the ideal nature of the recorded combustion products, with the compression ratio being negligible [15]. The formula for calculating the temperature after combustion of the premixed fuel is as follows [15]:

$$T_2 = T_{int} \cdot \frac{P_2}{P_{int}} \cdot M \quad (1)$$

Where:

T_2 : The temperature of the gas after pre-combustion.

P_2 : The pressure of the gas after pre-combustion.

T_{int} : The initial temperature of the gas.

P_{int} : The initial pressure of the gas.

M : The ratio of molecular mass between the combustion products and the gas mixture before combustion.

2.2 Data Acquisition and Indicating System

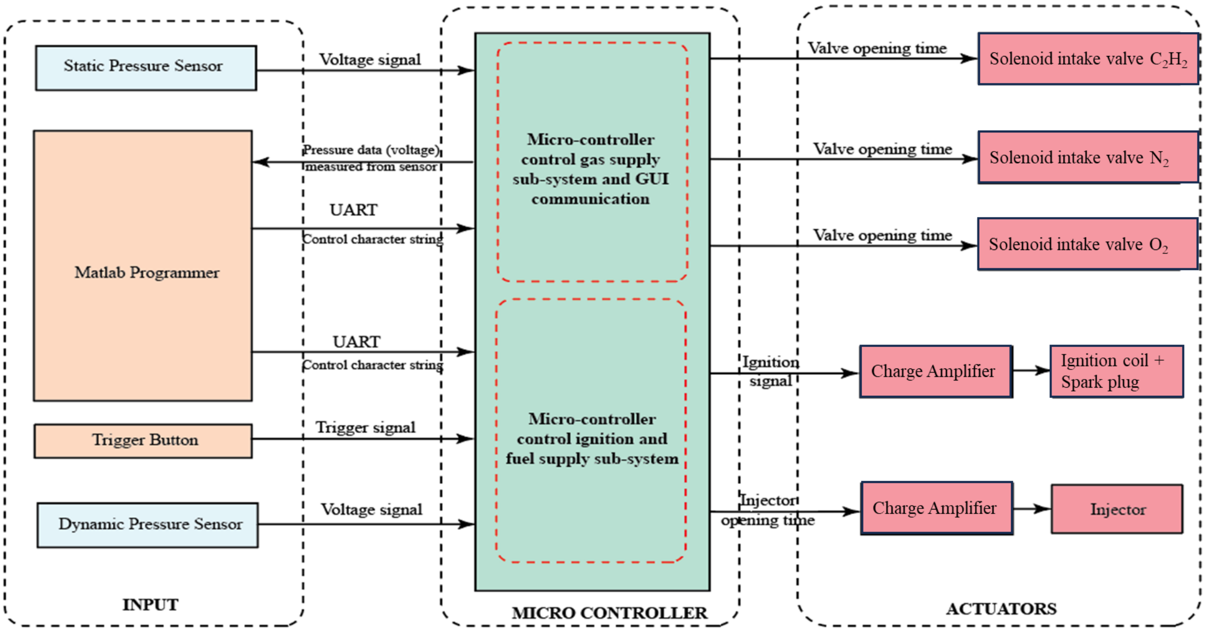


Figure 2: Schematic diagram of the control principle of the CVCC system.

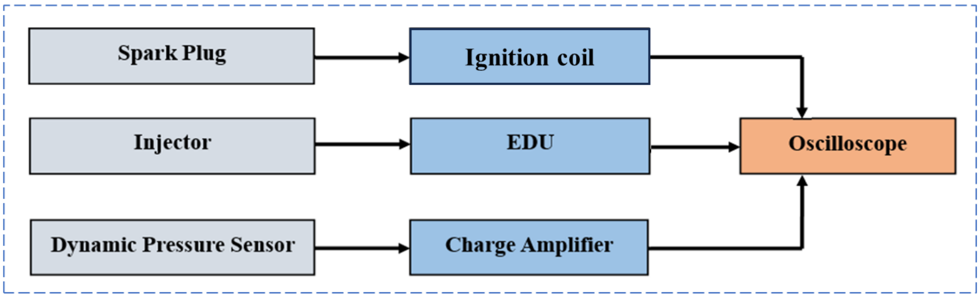


Figure 3: Principal diagram of the combustion process-indicator system.

The control of a CVCC system is based on the user providing input parameters to the processing control unit, which subsequently sends execution requests to the illustrated executing elements, as depicted in Figure 2.

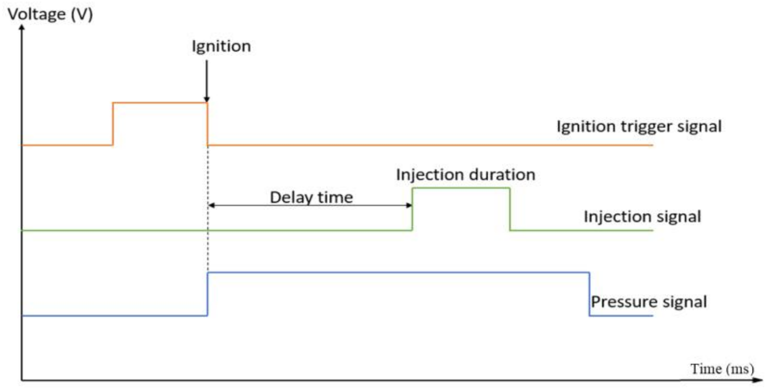


Figure 4: Logic diagram illustrating the interrelationship of control signal chains.

Figure 3 illustrates the schematic diagram of the process indicator system for combustion. The logic diagram in Figure 4 sketches the control signal chains, including the ignition signal and fuel injector activation signal used to program the combustion conditions similar to the compression phase in a diesel engine. The microcontroller is programmed to follow the sequence of control signals as illustrated in the timing diagram.

2.3 Control Method for Creating Premixed Combustible Mixture

Equation (2) represents the combustion reaction of the fuel-air mixture to produce 21% oxygen concentration after the reaction, along with generating high temperature and pressure. In this equation, the fuel-air mixture comprises C_2H_2, N_2, and O_2, adjusted in a balanced proportion through partial pressure. This 21% oxygen concentration is not considered as the exhaust gas recirculation (EGR) ratio, resembling the environment in a diesel engine before fuel injection. According to that, adjusting the ratio of the gas components before combustion can also create the desired excess oxygen concentration of 10% or 15% respectively.

$$\underbrace{3.5\%\ C_2H_2 + 67.1175\%\ N_2 + 29.3825\%\ O_2}_{\text{Pilot gas mixture}} \rightarrow \underbrace{7\%\ CO_2 + 3.5\%\ H_2O + 67.1175\% N_2 + 21\%\ O_2}_{\text{Product after ignition}} \quad (2)$$

The percentage of C_2H_2 in the initial mixture is selected as 3.5%, deemed appropriate based on the research conducted by P. Srichai et al. [16]. With an initial selected fuel-air mixture pressure of 14 bar, combined with the two given conditions and the reaction equation, the ratio of each gas component can be calculated, as shown in Table 1.

Table 1: Partial pressure values at a mixed pressure of 14 bar.

Desired oxygen concentration after ignition (%)	Partial pressure of each gas (bar)		
	C_2H_2	N_2	O_2
21	0.49	9.4	4.11
15	0.49	10.22	3.29
10	0.49	10.9	2.61

Figure 5 illustrates the general layout of a 3D combustible gas conditioning supply system and the corresponding signal control diagram. On the user interface, users input the calibration coefficients for the pre-reacted gas components, the desired $\%O_2$ after the reaction, and the pressure of the mixed combustible gas. The controller calculates the solenoid valve opening time for each gas component in the mixture. During the sequential loading process of each gas component, a static pressure sensor records and sends the readings to the monitoring screen. Figure 6 presents the gas loading control algorithm, and Figure 7 shows the sequence of solenoid valve control signals for the three gases C_2H_2, N_2, and O_2.

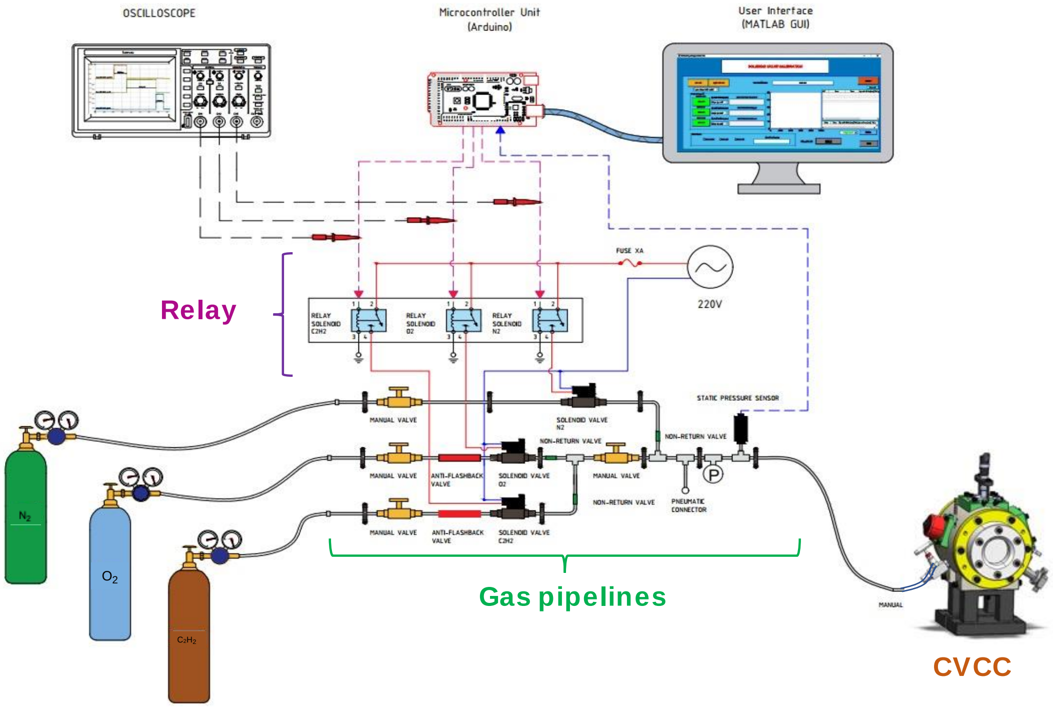


Figure 5: Signal control diagram and 3D structure of the air conditioning supply system

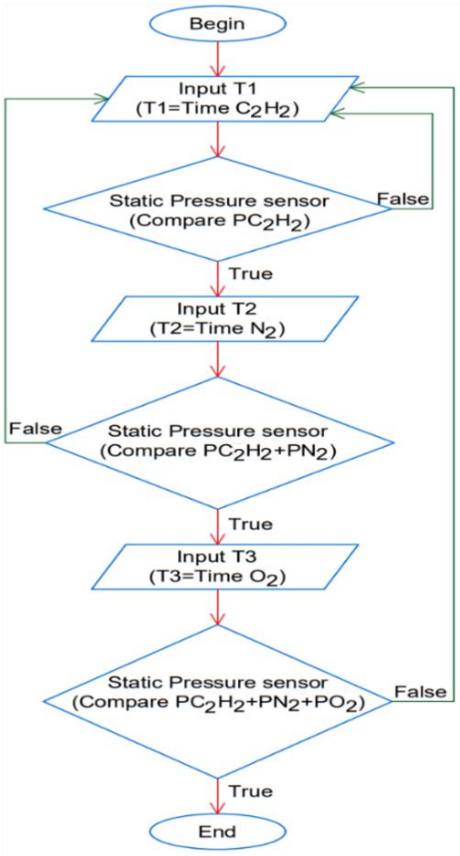


Figure 6: Gas loading control algorithm

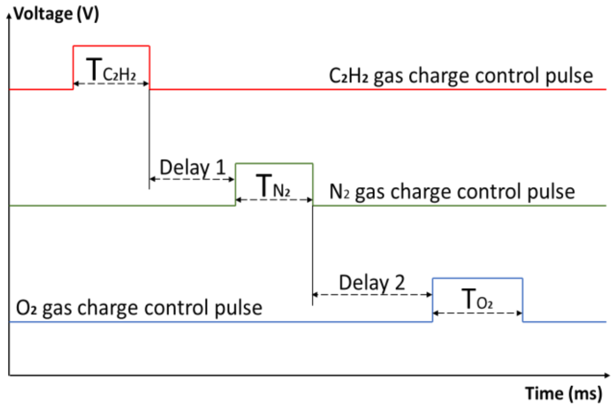


Figure 7: Sequence of solenoid valve control signals

3 EXPERIMENTAL SETUP AND TESTING CONDITIONS

Figure 8 and Figure 9 depict the schematic arrangement of the CVCC setup and the photograph of the experimental system, respectively. The combustion chamber was connected to the gas loading system via three gas cylinders containing C_2H_2, N_2, and O_2, along with a cluster of solenoid valves. A solenoid diesel fuel injector with 6 orifices was installed at the top of CVCC and connected to the high-pressure common rail fuel supply system. The air-fuel mixture inside the CVCC is evenly mixed and heated by the fan motor and the heater system installed around the exterior of the CVCC. The spark plug was positioned next to the exhaust valve to generate an electric spark that ignites the air-fuel mixture. To ensure safety during the experimental process, a rupture disc valve (code BP224) was installed at the bottom of the CVCC. The dynamic pressure sensor, type AVL-GU12P, was used to record the fuel combustion pressure inside the chamber. This signal would be amplified by a charge amplifier (Kistler code 5010B) and displayed synchronously with the spark plug and fuel injector signals on the oscilloscope.

Figure 8: The schematic arrangement of the experimental apparatus.

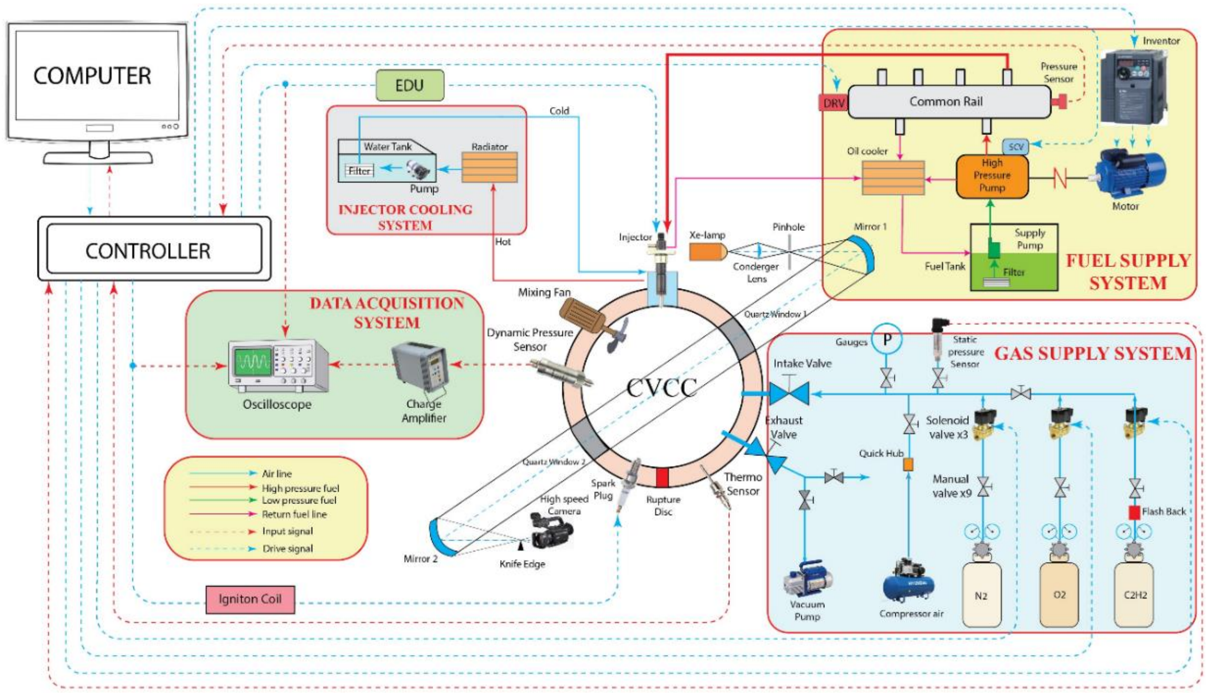
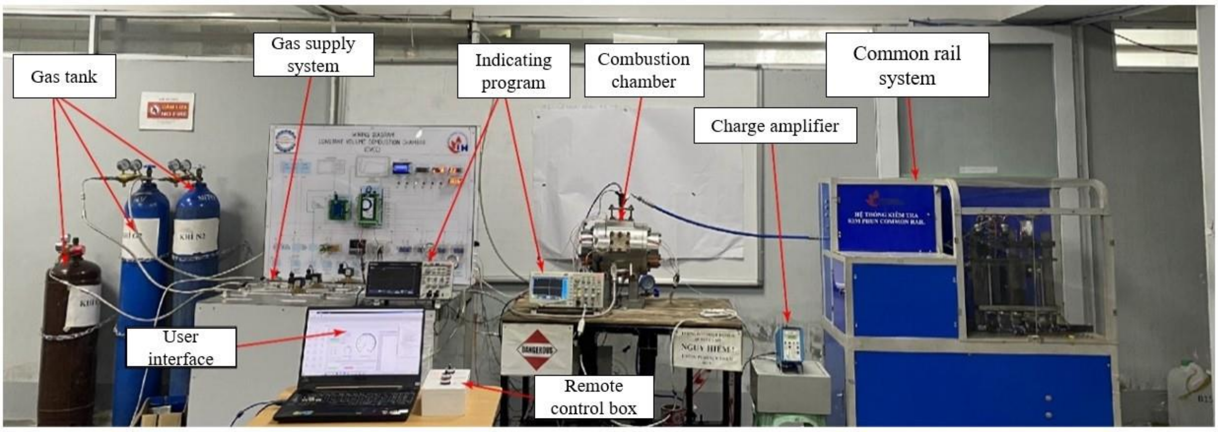


Figure 9: The photograph of the experimental setup.



To calibrate gas components, experiments determined solenoid valve opening times for C_2H_2, N_2, and O_2 gases at pressure ranges of 0-1 bar, 1-10 bar, and 10-17 bar. High-temperature, high-pressure generation experiments, and simulations of exhaust gas recirculation (EGR) conditions with 21%, 15%, and 10% oxygen concentrations during premixed combustion were conducted, as illustrated in Tables 1 and 2. In the case of a 21% oxygen concentration, diesel fuel injection was activated at a desired point on the pressure curve during the cooling down stage, corresponding temperature and pressure conditions in the CVCC system, which were 1100K and 45 bar, respectively. This is similar to the gas cylinder condition in a diesel engine with a compression ratio of 18.

Table 2: Experimental System Conditions

Parameters \ Details		Air intake conditions		
		C_2H_2	N_2	O_2
Combustible gas mixture pressure		14 bar		
Chamber wall heating temperature		90ºC		
Oxygen concentration before fuel injection		10%	15%	21%
Fuel injection conditions	Fuel pressure in Rail bar	1000 bar		
	Ambient pressure in chamber (diesel test)	45 bar		
	Ambient temperature in chamber (diesel test)	1100 K		
	Fuel injection length	2.0 ms		

4 RESULTS AND DISCUSSIONS

4.1 The Relationship between the Time of Air Intake and the Ratio of Gas Components

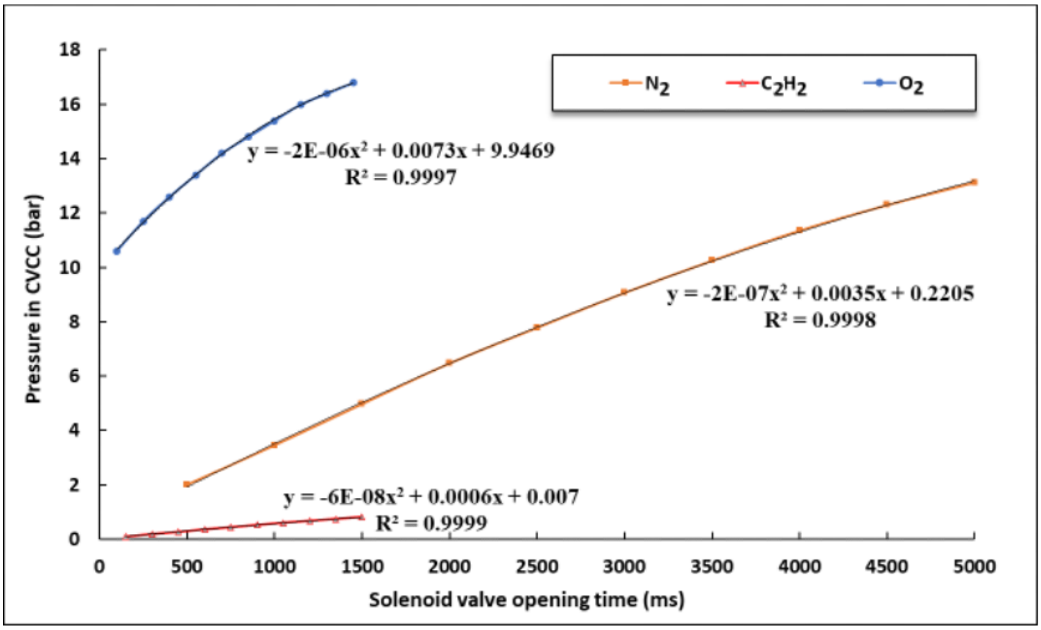


Figure 10: Calibration graph of three gases.

Figure 10 illustrates the gas intake adjustment graph for three gases—C_2H_2, N_2, and O_2—after combustion with 21% excess O_2, under a total pressure of 14 bar. The values were calculated using the corresponding composition ratios. Notably, the R^2 coefficients in each linear regression equation are consistently close to 1, affirming the high reliability and accuracy of this method. The time required to reach the partial pressures, as presented in Table 1, for the three gases C_2H_2, N_2, and O_2, are 883 ms, 3437 ms, and 679 ms, respectively. This graph is utilized to calculate the time needed to load the individual component gases when changing the values of pressure and temperature after the combustion to create an environment similar to the compression conditions of a diesel engine with 21% excess O_2 after the combustion reaction.

4.2 The Temporal Development of Pressure and Temperature during the Premixed-Combustion Phase

Figure 11 and Figure 12 illustrate the pressure and temperature variation during the premixed-combustion process of the combustible mixture in CVCC under three conditions: 10%, 15%, and 21% oxygen after ignition. Each condition was repeated 15 times, and the average peak pressure for each condition was 66.44 bar, 67.82 bar, and 69.51 bar, respectively. In terms of combustion temperature development, it is calculated using formula (1) based on pressure data recorded from the dynamic pressure sensor. The results from the

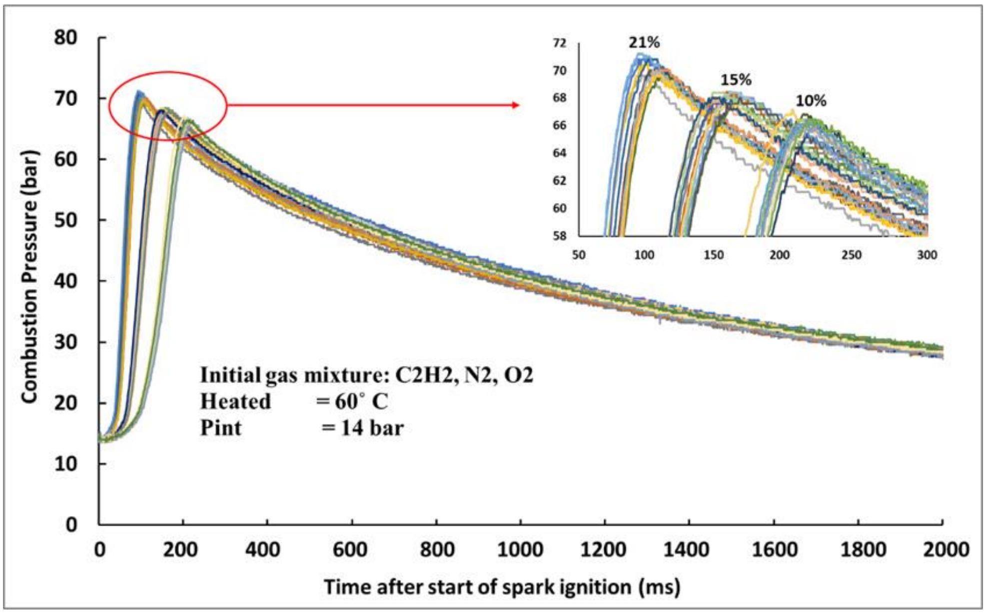


Figure 11: The temporal premixed-combustion pressure at 3 levels of oxygen concentration (10%, 15%, 21%)

two figures indicate that at higher levels of oxygen concentration after ignition, the fuel-air mixture burns more vigorously, leading to increased pressure and temperature in the combustion chamber. For a combustion chamber temperature of 1100K and pressure of 45 bar before diesel fuel injection, the calculated delay times at oxygen concentrations of 10%, 15%, and 21% after ignition are 740 ms, 713 ms, and 644 ms, respectively. Figure 13 displays the average integrated graph of peak temperature and pressure during the premixed-combustion stage in 15 tests for three oxygen concentration levels of 10%, 15%, and 21%. Examining the figure reveals that the average error levels for pressure and temperature in the CVCC combustion chamber under these three oxygen concentration conditions are 1.4% and 1.52%, respectively.

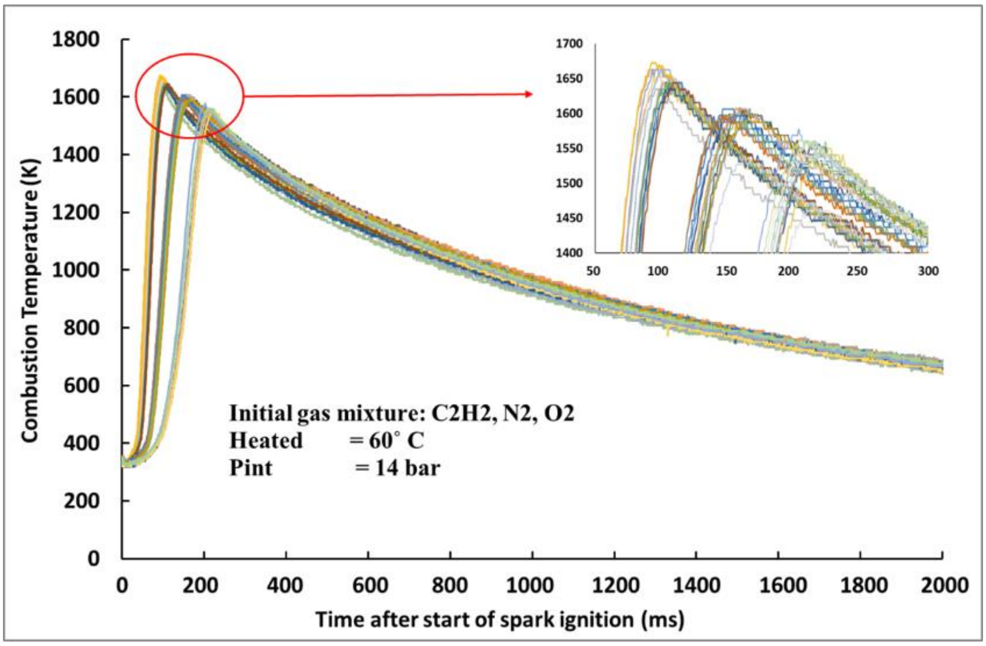


Figure 12: The temporal premixed-combustion temperature at 3 levels of oxygen concentration (10%, 15%, 21%)

Figure 14 represents the combustion pressure of diesel fuel inside the CVCC, while Figure 15 illustrates the heat release rate within the CVCC under the condition of 21% residual oxygen after ignition and an

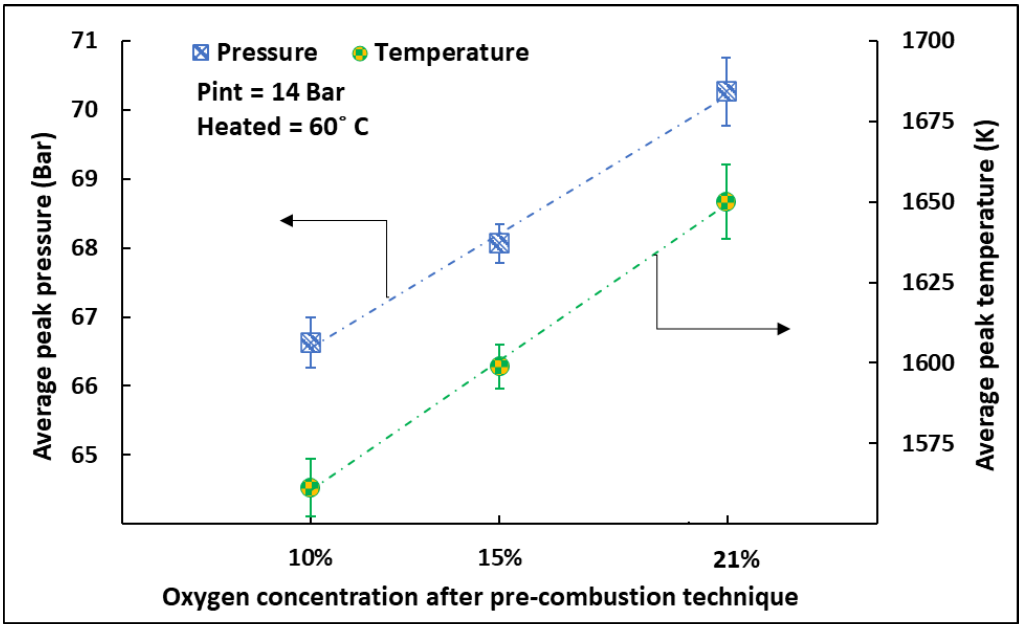


Figure 13: Average integrated graph of peak temperature and pressure under O_2 concentration (10%, 15%, 21%)

ambient temperature of 1100K. The delay time to activate the injector, as determined in Figure 12, is 644 ms, and the peak pressure during the combustible mixture-premixed combustion phase is 69.25 bar. The ambient pressure in the combustion chamber at the fuel injection point is 46.6 bar. This result exhibits a 3.5% error compared to the desired pressure specified in the experimental conditions table. In general, the appearance and shape of combustion and the heat release rate are observed to follow a similar trend as in other studies [18][19].

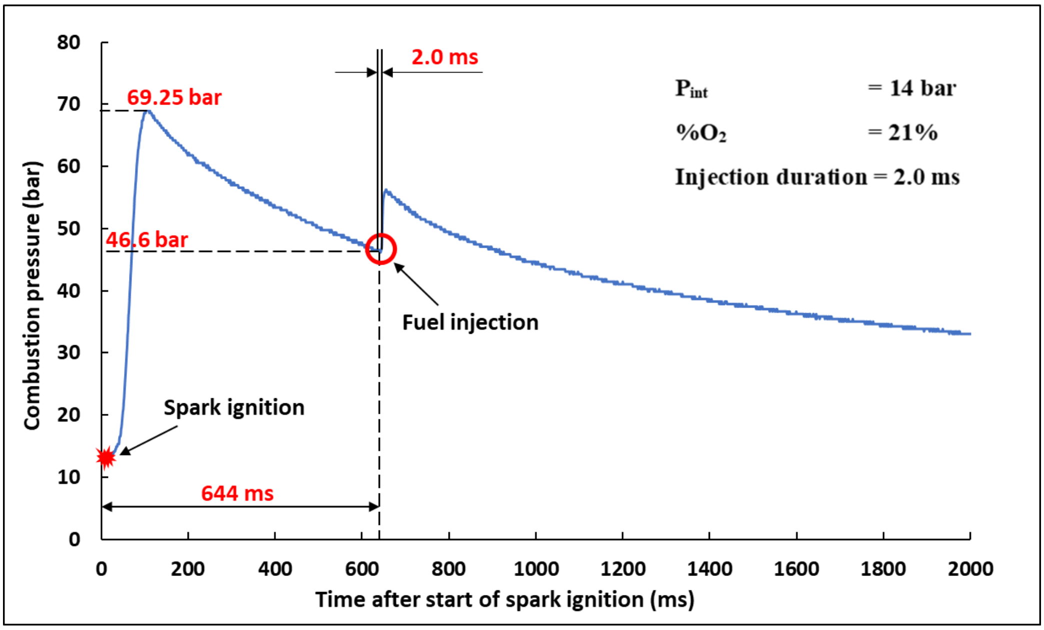


Figure 14: Combustion pressure graph of diesel fuel in CVCC at 3 oxygen concentration levels (10%, 15%, 21%)

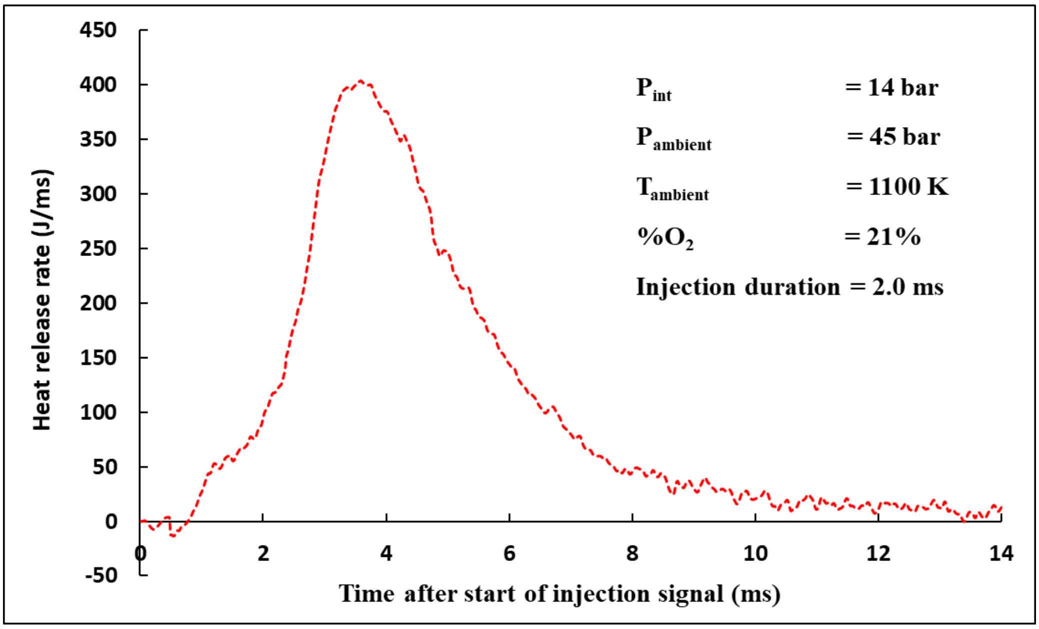


Figure 15: Heat release rate in CVCC.

5 CONCLUTIONS

This work developed algorithms to control signals from the gas charging system, spark plug, fuel injector, and dynamic pressure sensor in the CVCC system. The experimental determination of control accuracy in the CVCC system is implemented. Based on the analysis results, the following conclusions are drawn:

- The charging time for combustible gas components can be flexibly determined with high accuracy from the CVCC system, as evidenced by an R^2 coefficient approximately equal to 1.
- The control system aligns with the simulation conditions of exhaust gas recirculation, maintaining residual oxygen concentrations after the ignition reaction at 21%, 15%, and 10%, respectively.
- The control system for the premixed combustion stage generates operating conditions similar to the compression stage in a diesel engine, with an error in the maximum peak pressure of this stage of approximately 2.24% under experimental conditions.
- The control system is capable of conducting diesel fuel injection experiments under conditions resembling those of a diesel engine and recording the combustion process pressure of diesel fuel for the analysis of fuel combustion characteristics

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PHÁT TRIỂN HỆ THỐNG ĐIỀU KHIỂN – CHỈ THỊ CỦA BUỒNG CHÁY ĐẲNG TÍCH

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Tóm tắt: Nghiên cứu tối ưu quá trình cháy bằng hệ thống buồng cháy đẳng tích (CVCC) là một trong các phương pháp hiệu quả trong việc khảo sát các yếu tố ảnh hưởng đến quá trình cháy và sự hình thành khí thải của nhiên liệu ứng dụng trên động cơ đốt trong. Nghiên cứu này tập trung phát triển giải thuật điều khiển cho hệ thống CVCC dựa trên các tín hiệu đồng bộ từ bugi, cảm biến áp suất động, kim phun và ghi nhận dữ liệu theo thời gian thực để điều chỉnh tỷ lệ hỗn hợp khí mồi (C_2H_2, N_2, O_2) nhằm tạo ra được điều kiện hoạt động tương tự giai đoạn cuối kì nén trong động cơ diesel và mô phỏng hồi lưu khí thải. Ba nồng độ oxi sau phản ứng premixed combustion (cháy mồi) gồm 21%, 15%, 10% được lựa chọn để thực nghiệm trong CVCC trước khi giai đoạn phun nhiên liệu diesel bắt đầu tại áp suất hỗn hợp ban đầu là 14 bar. Kết quả cho thấy hệ thống đã điều khiển và ghi nhận dữ liệu đạt độ chính xác cao, độ sai số trong vòng 2.24% được nhận thấy khi phân tích giá trị áp suất cháy cực đại sau khi bugi được kích hoạt ở các nồng độ oxi thí nghiệm. Đồng thời các hệ thống điện tử hoàn toàn thực hiện theo đúng tín hiệu trigger và các tín hiệu điều khiển thời gian đã tính toán nhằm xác định tỷ lệ nồng độ khí mồi.

Từ khóa: Buồng cháy đẳng tích (CVCC), Hệ thống phun dầu điện tử (CRS), Hệ thống thu thập dữ liệu và điều khiển (DAC), Động cơ Diesel.

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