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Analysis of Hydrogen Enrichment in Gasoline Fueled Premixed Spark-Ignition Engine

Muzammil Arshad
Department of Mechanical & Aerospace Engineering
Florida Institute of Technology
Melbourne, FL, USA

Gerald J. Micklow
Department of Mechanical & Aerospace Engineering
Florida Institute of Technology
Melbourne, FL, USA

***Abstract*— Numerical simulations were performed in a direct injection spark ignition engine (DISI) with pentroof geometry. The study was performed for a premixed case with one-step gasoline global reaction mechanism and gasoline-hydrogen blends of 1%, 2% and 3% at equivalence ratios of 0.5 to 1. The purpose of the study was to analyze the combustion and thermal efficiency with and without hydrogen enrichment. The model was tested using a numerical simulation code that solves compressible, turbulent, three-dimensional transient equations. These equations apply to reacting multicomponent gas mixtures with flow dynamics of an evaporating liquid spray. The simulations performed a comparative analysis between the gasoline global mechanism and the gasoline/hydrogen global mechanism. The engine geometry used ø89.0 mm bore and 81.4 mm stroke, running at 2500 rpm. Earlier joint computational / experimental studies performed by the researchers have shown that injection a secondary fuel in small quantities in conjunction with the base fuel could lead to marked combustion process improvements and thermal efficiency. The secondary fuel had only a small contribution to the total engine heat release, but, it improved engine efficiency by increasing flame speed and ensuring a more complete combustion process for the base fuel. Hydrogen and oxygen enrichment in a small amount to the air-fuel charge results in efficient engine operation with lean air-fuel mixture. For lean fuel mixtures, peak combustion temperature decreases substantially. Without a substantial performance decrease, the lean or ultra-lean engine operation can be obtained with hydrogen injection. Hydrogen enrichment along with the lean burn engine conditions can produce acceptable operation with a marked reduction in fuel consumption and emissions under idle conditions, reduced loads and moderate acceleration. Results showed aggressive burning of gasoline while using hydrogen at all equivalence ratios. Addition of hydrogen encouraged complete burn of the fuel. Increase in indicated power, combustion efficiency, and thermal efficiency were observed with an increase in hydrogen percentage. The trend was visible during all hydrogen enrichments. With the increase in the hydrogen concentration, the average temperature and maximum temperature inside the cylinder slightly decreases. This is significant because as the percentage of hydrogen increases in the fuel, the result is higher efficiencies, complete combustion, and slightly lower temperatures inside the cylinder with fewer emissions.**

Keywords*— IC Engine; KIVA-3V; Direct Injection Spark Ignition (DISI); pentroof geometry; combustion efficiency; thermal efficiency; reaction mechanism.

I. INTRODUCTION

Understand the thermo-chemical phenomena involved in spark-ignition combustion is quite challenging. Considerable insight into the in-cylinder combustion dynamics can be achieved through computational simulation in conjunction with either collateral experiments or in comparison with published experimental data. The overall combustion-related performance of the engine is highly dependent on the in-cylinder fuel distribution and equivalence ratio. Instead of pure hydrogen powered engines, the concept of hydrogen enrichment to petroleum based fuels for use in internal combustions engines generates greater interest. The hydrogen enrichment does not require any major engine design changes and involves fewer modifications to the engines and their fueling system. For the proposed study, it is assumed that the hydrogen may be generated on-board the vehicle from electrolysis of water, and the required electricity is supplied by the vehicles charging system. It is expected that increases in engine efficiency will more than compensate for the energy loss incurred in generating the hydrogen. The proposed computational study will quantify the effect of different levels of hydrogen enrichment starting at zero percent up to the maximum percent allowable with an on-board hydrogen generation system based upon electrolysis.

A natural aspirated spark ignited direct injection gasoline engine operating at part load and full load conditions will be investigated in this study.

Work was done to develop a high pressure hydrogen injector for spark ignition (SI) engine [1]. An injection system was designed and used to supply hydrogen to a single cylinder SI engine. The designed injection system used two components: an injector and a pump. The results showed an improvement and a better performance than that achieved by only gasoline.

A gasoline engine was evaluated for its performance and parameters for various fuel types: gasoline and pure hydrogen, and gasoline and simulated reformer gas which contained H_2, CO, CO_2 and CH_4 [2]. Gasoline was injected into the cylinder while hydrogen or simulated reformer gas were introduced into the intake manifold. A commercial SI direct injection gasoline engine was modified to install an injection system of a commercial compressed natural gas (CNG) vehicle. The purpose of the study was to improve the thermal efficiency of a spark-ignition (SI) engine. Results showed an increase in thermal efficiency of the engine operated with gasoline and hydrogen or reformer gas rather than with the gasoline, under low and mid load conditions.

An experimental study was carried out on a 4-cylinder gasoline-fueled spark ignition (SI) engine. Hydrogen addition was used to study and improve engine idle performance [3]. Modifications were made to the existing engine to incorporate the gasoline-hydrogen fuel mixture. The fuel mixture was injected into the intake ports simultaneously. At stoichiometric and idle condition of engine, effects of multiple hydrogen enrichment levels on engine performance parameters such as thermal efficiency, engine speed fluctuation, combustion characteristics, cyclic variation and emissions were investigated. With the increase of hydrogen concentration, thermal efficiency, combustion performance, and NOx emissions increase. The HC and CO emissions decreased with increasing hydrogen concentration. The emissions showed an increase when hydrogen energy fraction exceeded 14.44%.

A similar study was also conducted with the experiments being performed with a pure gasoline-fueled engine and a hydrogen-enriched gasoline engine [4]. The hydrogen volume fractions were selected to be 1%, 3% and 5% in the total intake. The experimental study was conducted on an engine test bench at stoichiometric conditions. Results showed maximum brake mean effective pressure (BMEP) achieved at hydrogen volume fraction of 2%. The study concluded that at stoichiometric conditions, the combustion speed and quality of the in-cylinder mixture are effectively improved by hydrogen enrichment when hydrogen volume fraction in the intake is below 5%.

A proper hydrogen concentration of 2% does exist for maximizing the engine thermal efficiency under the specified test conditions. An experimental study was performed to improve the thermal efficiency and reduce emissions in SI engines. Stoichiometric air-fuel ratio was used at four intake manifold absolute pressures (MAP) of 39.3, 48.1, 56.4, and 67.8 kPa. The objective of the study was to improve SI engine performance under typical driving conditions of 1500 rpm [5]. The selected hydrogen volumetric fractions were 1%, 1.5%, 2%, and 3%. The SI engine used for the study was a modified 4-cylinder engine. An online mixing of hydrogen with gasoline is achieved by injecting hydrogen into the intake ports. Test results showed an average increase in brake thermal efficiency from 25.12% to 28.35%. These results were compared against the results obtained from original gasoline engine. Reduction in the cycle-by-cycle variation of the peak in-cylinder pressure was on average from 6.8% to 3.62%.

Hydrogen addition was used to reduce the fuel consumption and emissions [6]. The study was performed to improve the performance of a lean-burn SI engine. The engine was operating at low speed and load conditions. With fewer modifications, a hydrogen port-injection system was mounted on the intake manifold for a sequential introduction of hydrogen into the intake ports. The original gasoline injection system remained unmodified. Hydrogen was added in the volume fractions of 3%, 5%, 8% in the intake. Results showed an increase in engine brake thermal efficiency and torque output. Shortening of combustion durations and reduction in cyclic variation and HC were observed, but a NOx emission increased as hydrogen volume fractions was increased. On the other hand, reduction in CO emissions was observed.

Cold start performance of gasoline-fueled SI engine was experimentally investigated with an aim to improve it by hydrogen enrichment. For the purpose of conducting the experiments, a four cylinder, 1.6-L, SI engine was used. Hydrogen injection system was electronically controlled and mounted on the engine [7]. The engine was tested and started with the pure gasoline and gasoline-hydrogen blend at same conditions. Improvement in in-cylinder and indicated mean effective pressures were observed with hydrogen enrichment. Due to complete and enhanced combustion, reductions in HC and CO emissions were observed.

The effect of the addition of hydrogen-oxygen blends (hydroxygen) on the performance of a spark-ignited (SI) gasoline engine was investigated [8]. A modified SI engine was used to perform experiments with a hydrogen and oxygen port injection system. The engine was tested on three standard hydroxygen volume fractions of 0%, 2% and 4%. At lean conditions, test results showed an increase in thermal efficiency and brake mean effective pressure. This increase was achieved by using the hydroxygen-blended gasoline engine than the gasoline engines and gasoline-hydrogen engines. HC and CO emissions were reduced by using the standard hydroxygen engine. CO emissions were also found to be lower in the standard hydroxygen-enriched gasoline engine as compared to the hydrogen enriched gasoline engine. Increased NOx emissions resulted after addition of hydroxygen.

A comparative study of the experimental research was carried out on a spark-ignition (SI) single cylinder engine. The fuels used for the experiment were gasoline or only hydrogen. Tests were performed at 3000 rpm and at full load [9]. The obtained results showed that the hydrogen fueled engine provided the performance improvement. This was made possible because of the qualitative load adjustment.

A study on the effect of hydrogen enrichment in the gasoline-air mixtures was performed [10]. Engine performance and exhaust emission were used as performance parameters to evaluate a SI engine. A range of four air-fuel ratios, ranging from stoichiometric to lean were used. The hydrogen enrichment was varied; 0%, 2.14%, 5.28%, and 7.74% by volume. The experimental data was used to study the effect of hydrogen enrichment and addition on various engine performance parameters. Significant reduction in CO and HC emissions due to increase in air-fuel ratio was observed for the gasoline engine. Engine performance characteristics such as thermal efficiency and specific fuel consumption were improved with hydrogen addition. Addition of hydrogen to the gasoline-air mixture improved unburned HC emissions.

For SI engine, high efficiencies and low emissions of NO_x (oxides of nitrogen) are enabled by using hydrogen [11]. Even though there are performance advantages, there are many problems regarding the production, storage and distribution of hydrogen. Since hydrocarbons including gasoline fuel have a narrow flammability limit as compared to that of hydrogen, the gasoline-fueled engine can have a partial burn or misfire at lean mixtures. An effective way to improve the performance of SI engines at stoichiometric ratio and lean mixture is hydrogen enrichment. Effects of hydrogen enrichment and addition on the performance of SI engine were studied by performing experiments. Results showed stable engine operation at lean gasoline-hydrogen mixtures compared to the pure gasoline-fueled spark-ignition (SI) engine and an increase of engine output.

To improve IC engine performance, gasoline-hydrogen blend can be burned [12]. At lean gasoline-air mixtures, stable engine operation is made possible by addition of small quantities of hydrogen that results in increased flame speed at all equivalence ratios. Gasoline-hydrogen blend was used in a computational study using KIVA-3V to evaluate the performance of a SI engine. A dual fuel combustion model with gasoline and hydrogen one-step global reactions was used in the KIVA-3V code. Engine parameters such as indicated mean pressure and fuel consumption were studied to evaluate the performance of gasoline SI engine at part load operating condition. In addition, a study was conducted for evaluation the effects of operating SI engines at wide-open throttle. Equivalence ratio of air-gasoline mixture was varied at fixed hydrogen enrichment levels.

Gasoline SI engine with hydrogen enrichment was used to evaluate the performance by using a multidimensional code (KIVA-3V). The code was modified to model a hybrid combustion process for dual fuel [13]. The performance of the engine was evaluated at equivalence ratios of 0 to 0.6 and a speed of 1500 rpm. CFD calculations were carried out in order to predict the engine performance. Modified multidimensional KIVA-3V code release was used to model the turbulent combustion process of a multi-component fuel, while one-dimensional calculations were done to estimate the gas exchange processes. 3D simulations, starting at intake valve closing and ending at exhaust valve opening, were performed by means of the Kiva-3V code. Twelve chemical species were considered: gasoline (C_8H_{15}), H_2, O_2, N_2, CO_2, H_2O, H, O, N, OH, CO, and NO. The Kiva-3V code was modified to simulate the combustion of hydrogen, gasoline and carbon monoxide (the methane combustion was neglected).

The following reaction mechanism was considered:

$$2H_2 + O_2 \rightarrow 2H_2O \tag{1}$$

$$4C_8H_{15} + 47O_2 \rightarrow 32CO_2 + 30H_2O \tag{2}$$

$$2CO + O_2 \rightarrow 2CO_2 \tag{3}$$

A CFD analysis showed a higher efficiency using syngas and gasoline as fuel as compared to pure gasoline for the considered engine [13].

II. COMPUTATIONAL MODEL

The numerical simulations code used in the current study is the KIVA-3V [14] code developed by Los Alamos National Laboratory for numerical calculation of transient, two- and three-dimensional chemically reactive fluid flows with sprays.

The paper investigates premixed air-fuel mixture and the effects of small amounts of hydrogen in the reactant gases of a gasoline direct injection spark ignition (DISI) engine with pentroof geometry. A substantial amount of experimental research has been done on hydrogen injection in gasoline engines to increase the combustion and thermal efficiency. KIVA-3V was used to perform a comparative analysis between the gasoline global mechanism and gasoline/hydrogen global mechanism. Mesh independent study was performed for the engine geometry of ø89.0 mm bore and 81.4 mm stroke [15], running at 2500 rpm. The number of mesh cells used in the present study was 200,000. Table I and Fig. 1 below show the engine geometry.

TABLE I. ENGINE GEOMETRY SPECIFICATIONS

Compression Ratio	9.4
Bore [mm]	89.0
Stroke [mm]	81.4
Displacement	0.51L
Engine Speed [rpm]	2500
Ignition	30^o bTDC

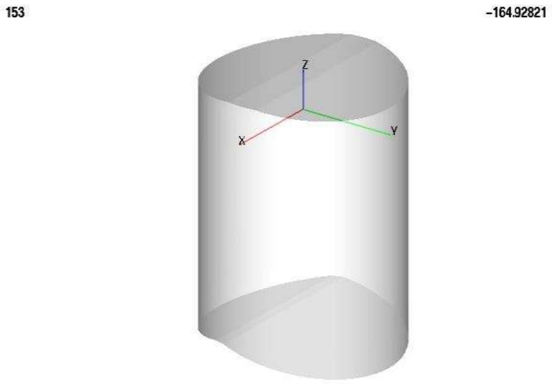

Fig 1. Engine Geometry

The analysis was performed at varying hydrogen inlet concentrations, i.e. 0%, 1%, 2% and 3%, with gasoline equivalence ratios ranging from 0.5 to 1. Global mechanism [16] uses the one-step fuel reaction mechanism along with the three reactions from the Zeldovich mechanism for prediction of NO_x formation. The chemical reaction equation for the global mechanism is:

$$4C_8H_{17} + 49O_2 \rightarrow 32CO_2 + 34H_2O \quad (4)$$

The global mechanism [16] uses a one-step reaction mechanism for the fuel, one-step mechanism of hydrogen with three reactions from the Zeldovich mechanism. The chemical reaction equation for the hydrogen mechanism is:

$$2H_2 + O_2 \rightarrow 2H_2O \quad (5)$$

The chemical reaction equations for the Zeldovich mechanism are:

$$2N_2 + O_2 \rightarrow 2N + 2NO \quad (6)$$

$$N_2 + 2O_2 \rightarrow 2O + 2NO \quad (7)$$

$$N_2 + 2OH \rightarrow 2H + 2NO \quad (8)$$

The analysis helped in determining the correct reaction mechanism to understand the chemical kinetics. Comparison analysis was performed between global gasoline and gasoline/hydrogen mechanism for engine parameters: in-cylinder pressure, heat release rate, fuel concentration and work done.

III. Results & Discussion

Numerical simulations are performed to investigate the variation between the engine parameters of in-cylinder pressure, work done and fuel concentration.

With the spark-ignition (SI) engine, the ignition option is turned on in the input file. The ignition option is controlled by a parameter that is the reciprocal time constant for ignition energy. For premixed case, the nominal ignition angle is 30^o bTDC for equivalence ratios of 0.5 to 1.0. Fig. 2 to Fig. 7 shows the fuel concentration before and during the combustion. Since it is a comparison between single component fuel and dual fuel, Fig. 2 to Fig. 7 shows the equivalence ratio of 0.5 to 1 and a hydrogen concentration of 0%, 1%, 2% and 3%.

TABLE II. Engine Efficiencies At Various Equivalence Ratios

Hydrogen Conc. (%)	***Equivalence Ratio (ϕ)***	***Combustion Efficiency (η_{comb})***	***Thermal Efficiency (η_{th})***	***Indicated Power (kW)***
0 %	0.5	90.19	33.48	6.6
	0.6	92.32	34.06	8.04
	0.7	92.54	32.35	8.89
	0.8	95.79	34.57	10.85
	0.9	96.01	33.49	11.8
	1.0	97.24	33.08	12.93
1 %	0.5	95.52	38.86	7.8
	0.6	96.96	37.94	9.14
	0.7	99.95	40.6	11.36
	0.8	98.53	36.5	11.63
	0.9	99.08	35.74	12.77
	1.0	99.48	35.03	13.87
2 %	0.5	99.99	45.97	9.49
	0.6	99.99	44.29	10.88
	0.7	99.99	42.76	12.17
	0.8	99.99	41.3	13.36
	0.9	99.98	39.78	14.4
	1.0	99.87	38.94	15.6
3 %	0.5	99.99	48.58	10.25
	0.6	99.99	46.22	11.56
	0.7	99.99	44.39	12.83
	0.8	99.99	42.59	13.96
	0.9	99.98	40.94	15.01
	1.0	99.01	38.92	15.77

Results in Fig. 2 to Fig. 7 show aggressive burning of gasoline-hydrogen blend at all equivalence ratios. Addition of hydrogen encouraged complete burn of the fuel. Increase in indicated power, combustion efficiency and thermal efficiency was observed with increase in hydrogen percentage. The increase in the above quantities is evident in all hydrogen concentrations. Although the peak value of average temperature and maximum temperature in the cylinder increases with the increase in the hydrogen concentration, the average temperature and maximum temperature inside the cylinder slightly decreases at the end of the power stroke at higher hydrogen concentrations. This is significant because as the percentage of hydrogen increases in the fuel, there are higher efficiencies, complete combustion, and slightly fewer temperatures inside the cylinder by the end of the power stroke, which means fewer emissions. Table II above shows the combustion and thermal efficiencies along with the indicated power. Results from Table II are also confirmed by the trend of thermal efficiency shown for methane-hydrogen blend in [17].

The fuel concentration plots obtained from the simulations show complete burn of the dual-fuel at all equivalence ratios. Gasoline as a single-component fuel does not show a complete burn. Although both cases use the same ignition energy, dual-fuel depicts combustion efficiency very close to 100%. This trend shows that addition of hydrogen at all equivalence ratios encourages more combustion of gasoline. This, in turn, increases the thermal efficiency of the engine. Below are the fuel concentration plots at all of the above-mentioned equivalence ratios.

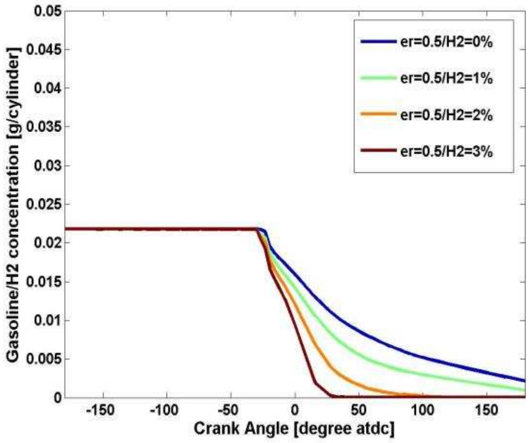

FIG 2. FUEL CONCENTRATION AT EQUIVALENCE RATIO OF 0.5 – PREMIXED

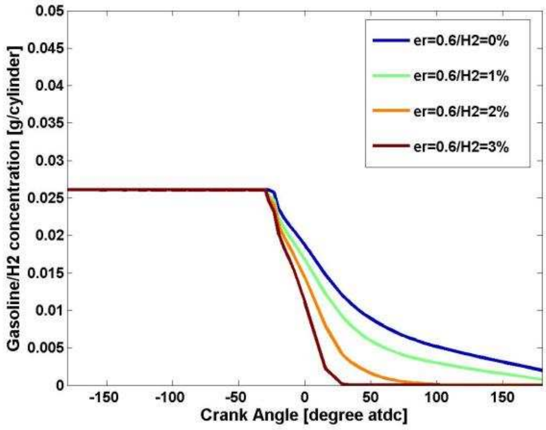

FIG 3. FUEL CONCENTRATION AT EQUIVALENCE RATIO OF 0.6 – PREMIXED

Fig. 2 to Fig. 7 shows the comparison of gasoline concentration as a single component fuel and gasoline/hydrogen concentration as a dual fuel. The figures show the fuel concentration before and during the combustion for ϕ = 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0.

For all equivalence ratios, the dual fuel burns completely for the hydrogen concentration of 2% and 3%.

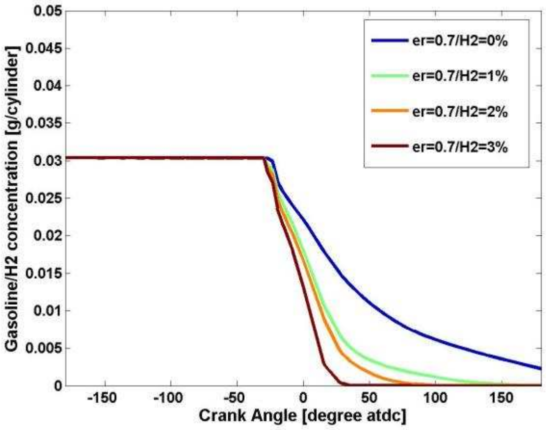

FIG 4. FUEL CONCENTRATION AT EQUIVALENCE RATIO OF 0.7 – PREMIXED

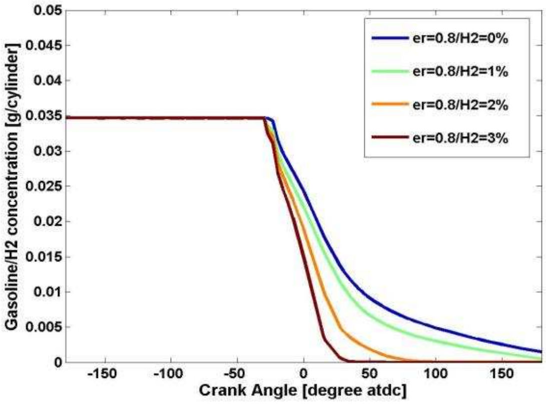

FIG 5. FUEL CONCENTRATION AT EQUIVALENCE RATIO OF 0.8 – PREMIXED

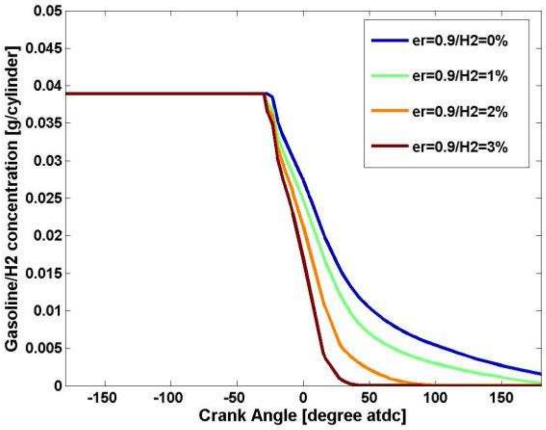

FIG 6. FUEL CONCENTRATION AT EQUIVALENCE RATIO OF 0.9 – PREMIXED

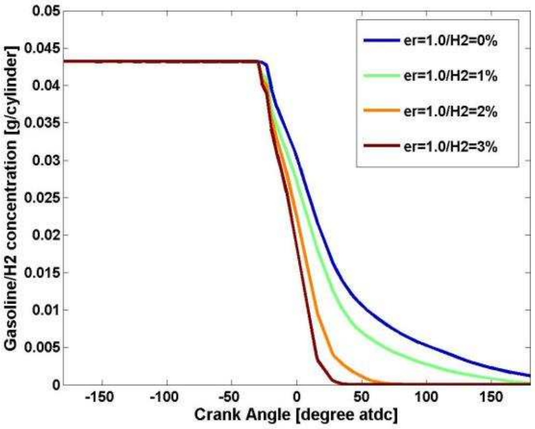

FIG 7. FUEL CONCENTRATION AT EQUIVALENCE RATIO OF 1.0 – PREMIXED

The plots from Fig. 8 to Fig. 13 show the work envelope. The PV diagrams obtained show a larger enclosed work envelope for the dual-fuels at higher hydrogen concentrations than the single-component gasoline fuel. The work envelope is highest for the 3% hydrogen addition case. This shows that adding hydrogen has proved to be beneficial and will help in the getting more work output from the spark ignition engine.

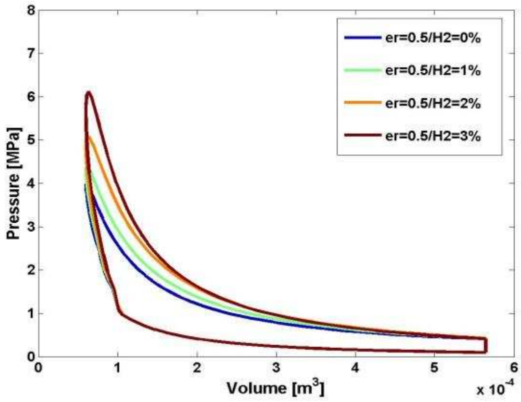

FIG 8. WORK DONE AT EQUIVALENCE RATIO OF 0.5 – PREMIXED

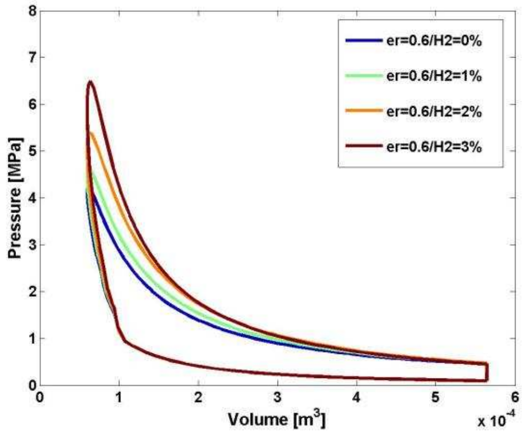

FIG 9. WORK DONE AT EQUIVALENCE RATIO OF 0.6 – PREMIXED

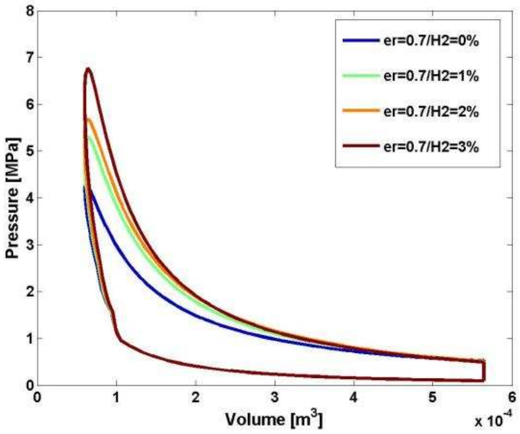

FIG 10. WORK DONE AT EQUIVALENCE RATIO OF 0.7 – PREMIXED

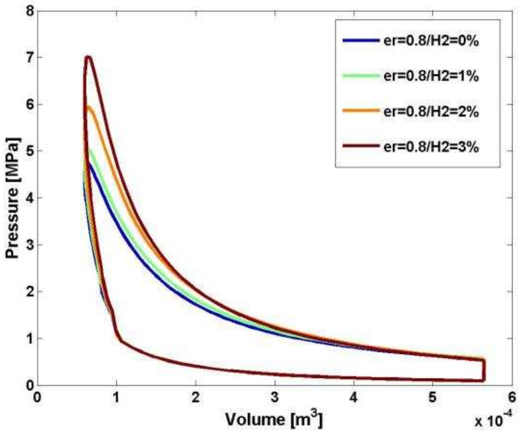

FIG 11. WORK DONE AT EQUIVALENCE RATIO OF 0.8 – PREMIXED

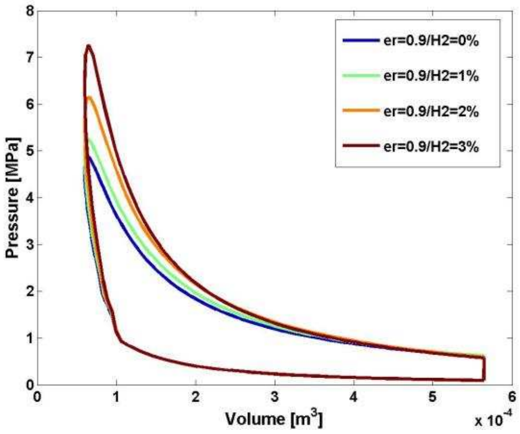

FIG 12. WORK DONE AT EQUIVALENCE RATIO OF 0.9 – PREMIXED

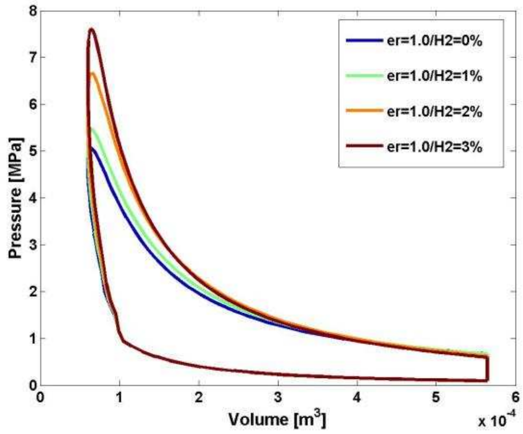

FIG 13. WORK DONE AT EQUIVALENCE RATIO OF 1.0 – PREMIXED

A. Temperature Plots - Comparison of Global Gasoline Mechanism and Gasoline/Hydrogen Mechanism at $\phi = 0.5$ to $\phi = 1.0$:

The simulation results obtained using KIVA-3V is post-processed to construct temperature plots. The plots in *Fig. 14* to *Fig. 19* show the combustion results from the ignition stage to the complete burn for the premixed case at equivalence ratio of 0.5 to 1.0 for both single component gasoline and dual fuel reaction mechanisms.

The plots show an increase in the temperature of the premixed fuel with ignition. They show the temperature increase throughout the engine cylinder as the temperature rises after the ignition of the fuel mixture. The plots demonstrate at all equivalence ratios, the dual-fuel mixture with 3% hydrogen addition burns faster and hotter similar to the fuel concentration plots that showed the same result in terms of a complete burn.

For equivalence ratios of 0.5 to 1.0, Fig. 14 to Fig. 19 below shows a comparison of ignition and fuel burn at hydrogen concentrations of 0%, 1%, 2% and 3%.

IV. CONCLUSION

A comprehensive study was performed for a detailed analysis of combustion efficiency, thermal efficiency, indicated power, fuel concentration and temperature plots. The criterion of this study was to ensure high combustion efficiency. This study provided detailed information on a premixed single-component fuel and on dual-fuel cases. Addition of hydrogen in the premixed case showed a trend of increase in the combustion efficiency, thermal efficiency, indicated power and encouraged a complete burn of the fuel mixture in the engine. The temperature decrease at high concentrations of hydrogen implies low emissions. It shows that if a small amount of hydrogen is premixed with gasoline, it will encourage a complete burn which will burn the entire fuel vapor, thereby making it a cost effective process, and will reduce the emissions.

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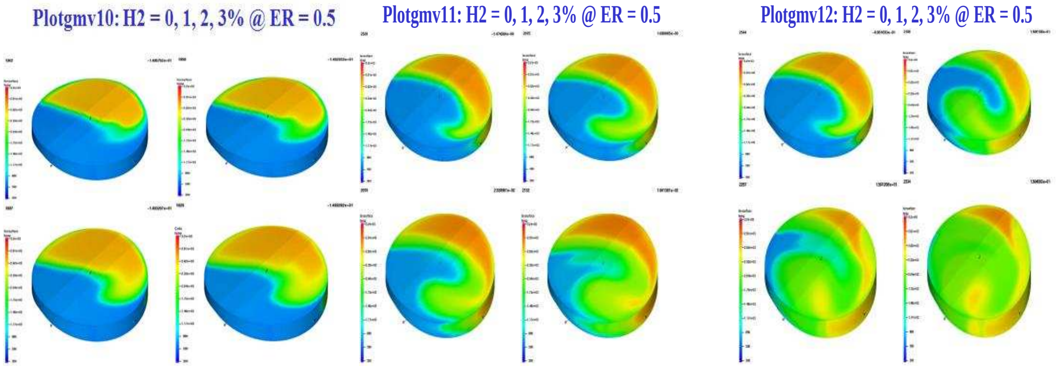

Fig 14. Temperature Progression After Ignition At Equivalence Ratio Of 0.5

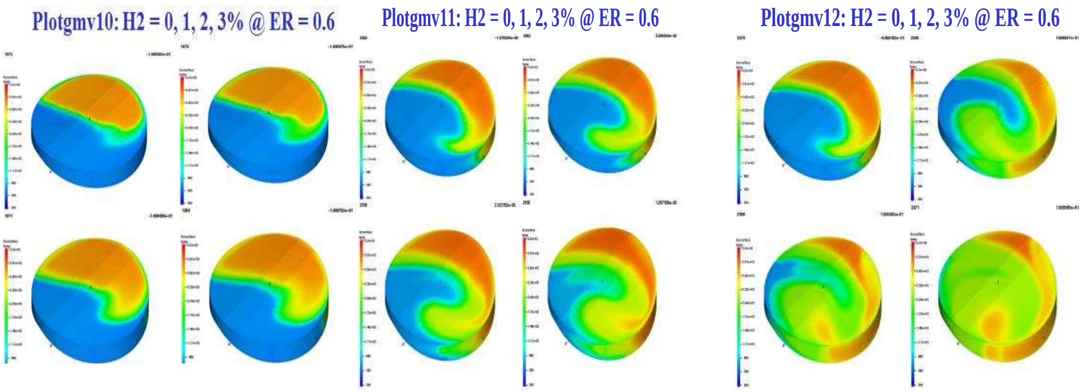

Fig 15. Temperature Progression After Ignition At Equivalence Ratio Of 0.6

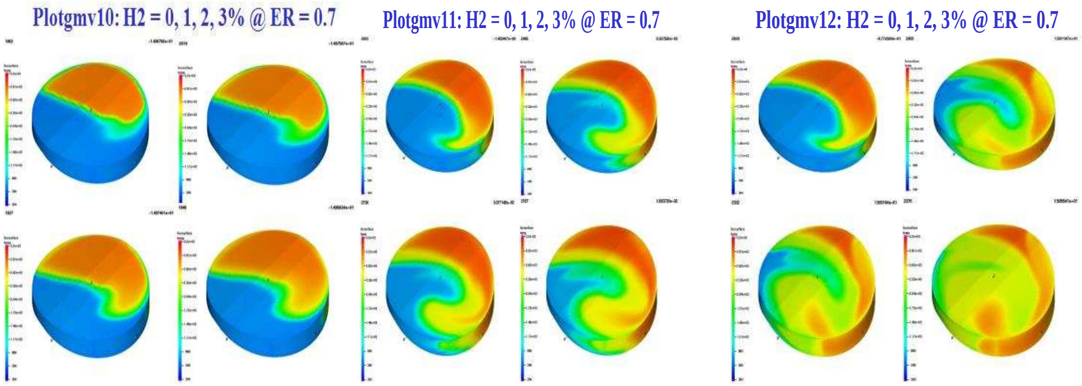

Fig 16. Temperature Progression After Ignition At Equivalence Ratio Of 0.7

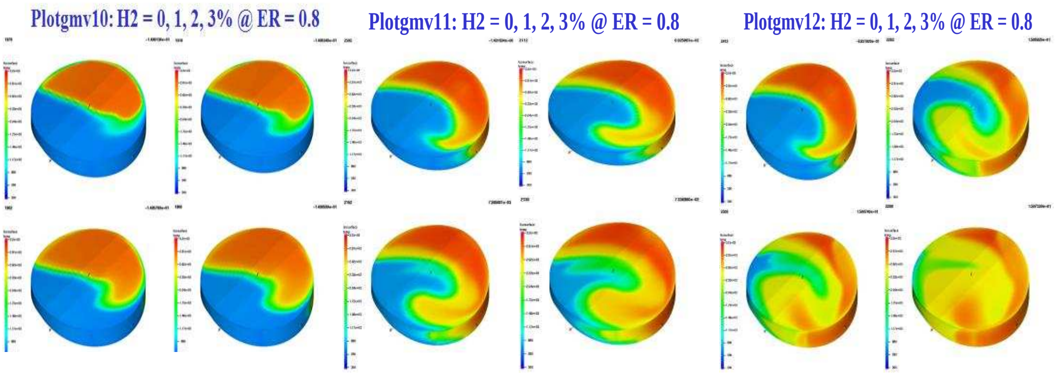

FIG 17. TEMPERATURE PROGRESSION AFTER IGNITION AT EQUIVALENCE RATIO OF 0.8

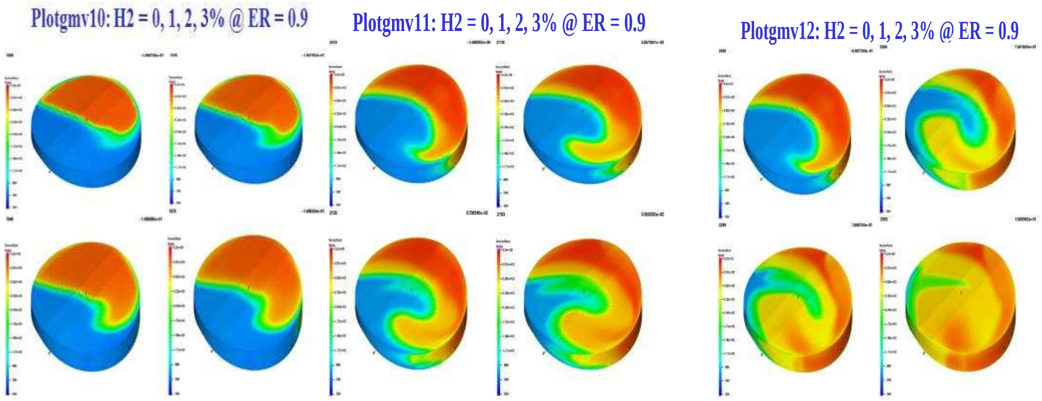

FIG 18. TEMPERATURE PROGRESSION AFTER IGNITION AT EQUIVALENCE RATIO OF 0.9

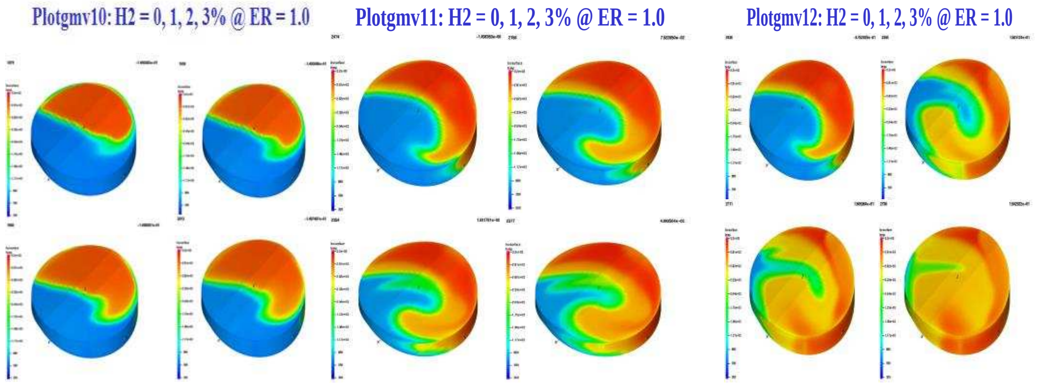

FIG 19. TEMPERATURE PROGRESSION AFTER IGNITION AT EQUIVALENCE RATIO OF 1.0