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Performance and In-cylinder Combustion Analysis of Gasoline Ethanol Fueled Spark-Ignition Engine

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ABSTRACT

Ethanol is widely recognized as a sustainable and eco-friendly alternative for spark-ignition (SI) engines, primarily due to its renewable nature and favorable combustion characteristics. This study investigates the impact of ethanol-gasoline blends on the performance of a 1.2L naturally aspirated, SI, multi-point fuel injection engine, tested under standard temperature and pressure (STP) conditions. The study focuses on three fuel blends: pure gasoline (E0), E10 (10% of ethanol), and E20 (20% of ethanol). Experimental evaluations were conducted using a state-of-the-art engine test laboratory to assess key performance parameters, including in-cylinder combustion parameters, fuel consumption, exhaust temperature, and power output. The engine was tested at full throttle for rated speed, maximum torque, and lower speed conditions. The results indicate that E20 fuel provides improved combustion efficiency compared to E0 and E10, which is attributed to its higher oxygen content and enhanced flame propagation characteristics. At the same time, it is also important to note that E20 exhibited lower brake thermal efficiency (BTE) and higher brake-specific fuel consumption (BSFC) relative to the other blends, likely because of its lower energy density. Key findings include higher peak HRR and improved combustion stability for E20 compared to E0 and E10. While E20 shows promise in terms of combustion dynamics, the trade-offs in fuel consumption and thermal efficiency warrant further investigation. Overall, this research contributes valuable insights into the impact of ethanol blending on SI engine performance, informing future fuel development strategies aimed at enhancing efficiency in reciprocating combustion engines.

1. INTRODUCTION

Recently, there has been a shift of focus about the utilization of bio-ethanol as an alternative fuel for reciprocating engines. The increased focus is motivated by issues including autonomy, the need for energy security, the necessity to diminish greenhouse gas emissions, and the economic benefits it provides to local agriculture and other sectors. Despite the discovery of new unconventional energy sources, gasoline remains the prime energy source in India due to supply-demand imbalances in other forms of commercial energy. Ethanol is poised to emerge as the most feasible alternative fuel in the Indian context in the near future. This preference is attributed to its production from "cellulosic biomass," representing a zero-emission technique that absorbs a significant amount of CO_2 during production. Additionally, ethanol, made up of molecules that include a hydroxyl group attached to a carbon atom, promotes additional combustion of gasoline. The domestic production of ethanol not only reduces the burden on import duties but also creates substantial opportunities for rural employment. Countries including Sweden, Brazil, and the USA have achieved substantial advancements in the domain of alcohol-gasoline-based alternative automotive fuels. They have developed variable fuel vehicle technologies and have utilized ethanol-gasoline mixtures up to E85. India, constrained by economic and environmental concerns, has mandated the compulsory use of E10 as fuel in light-duty vehicles. Ethanol, a renewable biofuel derived from biomass, has performance characteristics such as built-in oxygen content, a greater octane rating, and a higher latent heat of vaporization, which enable enhanced power output from both modified and unmodified engines. The advantages of biofuels include mitigating the energy dependence on oil resources, promoting a cleaner combustion process, and contributing to the reduction of CO_2 concentration in the atmosphere. The utilization of ethanol blends, specifically E10 and E20, in internal combustion engines is deemed suitable due to their balance between performance and environmental benefits. As a renewable fuel, ethanol helps lower greenhouse gas emissions in comparison to traditional gasoline. Nevertheless, existing research indicates that ethanol blends exceeding 20% lead to an increase in BSFC and have adverse effects on engine performance. The decline is mainly due to the lower energy content of ethanol compared to gasoline, which leads to increased fuel injection to obtain equivalent power outputs [1, 2]. Increased unregulated emissions of aldehydes and particulate matter have been widely documented, raising significant environmental concerns regarding higher ethanol blends [3]. Higher ethanol concentrations also pose material compatibility problems when used in existing engines. Due to the fact most vehicles on the road today cannot handle ethanol blends higher than 20%, using higher ethanol blends may cause the rubber seals and gaskets to deteriorate and may require engine component changes [4]. Consequently, it is essential to examine the impacts of lower ethanol blends like E10 and E20, particularly in India, where the use of E20 has been mandated. This analysis is crucial for ensuring that the company complies with or surpasses regulatory standards, as well as for gaining insights into the performance and emissions of these blends in the current fleet of vehicles on the road. The primary objective of this study is to explore the performance attributes of ethanol-gasoline blends in a conventional spark ignition (SI) engine that is intended for gasoline use. As a fuel, ethanol has been chosen because it has positive attributes and there is currently sufficient infrastructure in India to support its use. Due to this, there is a large surplus of ethanol production in the country that is well matched to the legislative requirements for using the product in fuel blends, which can help in the easy shift to renewable energy. On the other hand, other biofuels for instance, methanol have their own drawbacks which make them unsuitable for use in the current context, for instance, an increase in the level of NOx emissions due to their high density and oxygen content that may worsen air pollution [5]. Additionally, methanol has a lower heating value (LHV) compared to ethanol, indicating that a greater quantity of fuel is required to generate the same amount of energy [6]. Moreover, because of the high auto ignition temperature of methanol, increased compression ratios are needed, however, this makes it not compatible with most current engines without alterations [4]. However, methanol is hard to handle and is also toxic. Considering these factors, the authors contend that ethanol is a superior option compared to other alcohol-based fuels and biofuels for this study, as it aligns with performance requirements and complies with legal standards.

The next section provides a concise literature review to examine the opportunities and challenges related to higher ethanol concentrations in ethanol-gasoline blends.

2. LITERATURE REVIEW

Saikrishnan et al. [7] examined the impact of ethanol-gasoline blends (E0, E5, and E15) on the performance and emissions of a four-stroke, three-cylinder SI engine, using E0 as a benchmark. The study assessed various parameters, including mechanical efficiency, BTE, and specific fuel consumption, as well as emissions of carbon monoxide (CO), hydrocarbons (HC), carbon dioxide (CO_2), and nitrogen oxides (NOx), under different torque conditions while keeping the engine speed constant. The results indicated that the use of ethanol-gasoline blends led to increases in BTE, brake power, and fuel consumption. Meanwhile, emissions of CO and HC were reduced, while NOx emissions showed an increase with the ethanol-gasoline blends.

Nwufo et al. [8] conducted a comprehensive study on a single-cylinder spark ignition engine operating on ethanol-gasoline blends. The research investigated various ratios of ethanol-gasoline blends, assessing combustion characteristics, exhaust emissions (HC, CO, O_2, and CO_2), and engine performance metrics including brake power, engine torque, brake-specific fuel consumption, BTE, and brake mean effective pressure. Tests performed at full load across different engine speeds revealed that incorporating ethanol into gasoline improves combustion efficiency and substantially lowers emissions, resulting in enhanced engine performance.

In their experimental investigation, Srinivas Rao et al. [9] investigated the effects of fuel additives on the performance and emission characteristics of a spark ignition engine operating on petrol. Toluene, benzene, and ethanol were used as fuel additives at a concentration of 20% by volume. Performance assessments carried out on a single-cylinder, four-stroke stationary gasoline engine showed that ethanol-blended gasoline outperformed pure gasoline, especially under higher load conditions. While toluene exhibited marginally lower performance at lower loads, it demonstrated enhanced performance relative to pure gasoline at higher loads. Conversely, benzene consistently demonstrated poor engine performance across all load values. The short-term experimental results suggested the successful substitution of petrol with 20% toluene or 20% benzene additives without necessitating alterations in engine design.

An overview of the effects of mixing gasoline and ethanol for usage in spark ignition engines was given by Stein et al. [10]. The study found that the high latent heat of vaporization (HoV), research octane number (RON), and sensitivity of ethanol contribute to a substantial enhancement in knock resistance when its proportion in an ethanol-gasoline blend is increased. Nevertheless, in-use SI engines are unable to fully utilize the fuel's knock resistance due to their limitation caused by peak cylinder pressure (Pmax) at higher loads. As a long-term fuel, a mid-level blend of ethanol (more than E20 and less than E40) seems appealing.

Pal [11] focused on the emissions and performance of a four-cylinder SI engine equipped with a multi-point fuel injection (MPFI) system while using various ethanol-gasoline blends (Gasohol). It assessed multiple performance indicators, including thermal efficiency and brake power, as well as exhaust emissions such as CO, HC, NOx, and CO_2. The findings suggest that low-ethanol blended gasoline can act as a cleaner fuel, significantly reducing CO, HC, and NOx emissions. Performance metrics indicated improvements in both power and thermal efficiency, along with a slight increase in specific fuel consumption. However, there was also an increase in exhaust gas temperature and peak cylinder pressure, which underscores the benefits of the natural oxygen content present in ethanol molecules.

Delvi et al. [12] conducted an experimental study on the performance, emissions, and combustion characteristics of different ethanol-gasoline (Gasohol) blends, specifically E25, E30, and E35, using a single-cylinder spark ignition engine. Tests with different loads, engine speeds, and compression ratios were run, and the outcomes were noted. The outcome demonstrated enhanced engine performance metrics. It was found that ethanol-gasoline blends exhibit greater thermal brake efficiency compared to gasoline. The E35 blend achieved a maximum BTE of 27.87%.

In an investigative study conducted by Al-Hasan [1], in which a single-cylinder, naturally aspirated, four-stroke spark ignition engine was evaluated using gasoline blended with ethanol at various concentrations (2.5%, 5%, 10%, 15%, and 20%). The engine's performance was assessed and compared to its operation on pure gasoline. Under stoichiometric conditions, increasing the ethanol content led to a rise in indicated engine power, while indicated specific energy consumption (ISEC) showed a slight reduction.

Therefore, it is clear that researchers have thoroughly examined the effects of ethanol-gasoline blends on engine performance and combustion parameters. Nevertheless, the authors of the current study propose that a complete understanding of gasoline-ethanol blends in engines can be attained by conducting an in-depth analysis of both engine performance and combustion characteristics. This method seeks to offer a more comprehensive view of the topic.

2.1 Latest technological advancements for ethanol-blended gasoline

In this paper, Purayil et al. [13] performed a thorough analysis of how ethanol-gasoline and methanol-gasoline blends affect the performance of lean-burn spark ignition engines, particularly focusing on the knock limit related to ethanol-enriched fuels. The results indicate that the addition of ethanol and methanol to gasoline raises the hydrogen knock limit, especially in cases of retarded spark timing. However, this method also results in a decline in BTE and peak in-cylinder pressure. Furthermore, while these blends reduced CO_2 and NOx emissions, they led to an increase in CO emissions, highlighting the connection between engine performance, fuel type, and environmental consequences.

In the context of increasing environmental regulations and the necessity to enhance air quality, Meng et al. [14] addressed the significant issue of vehicle exhaust emissions. The study aimed to investigate the role of engine oil as a contributor to environmental pollutants during the operation of motor vehicles and emphasized the importance of evaluating its impact on emissions when used with gasoline, ethanol, and E85 fuels. The research examined the effects of new engine oil (NEO) and waste engine oil (WEO) in various proportions on emissions. The results indicated that the inclusion of engine oil notably elevated the emissions of carbon monoxide (CO) and particulate matter. For example, adding 1% NEO to E85 fuel resulted in a 25% increase in CO emissions, along with increases of 4.91% in particulate matter (PM) and 2.23% in particle number (PN). Additionally, the study utilized thermogravimetric analysis (TGA) and scanning electron microscopy (SEM) to investigate the pyrolysis of engine oil and the ash morphology resulting from combustion, respectively. These findings underscored the necessity for further research on the effects of engine oil on pollutant emissions when utilizing ethanol-blended fuels.

Zhao et al. [15] examined the optimization of a multifuel combined supply system that can utilize ethanol, gasoline, and oxyhydrogen to enhance engine performance and lower emissions. The results indicated that the stratified combustion achieved with ethanol direct injection (EDI) is superior to that of gasoline direct injection (GDI). The use of oxyhydrogen negative pressure inhalation (ONPI) increased both the maximum pressure and the indicated mean effective pressure (IMEP), while reducing emissions of CO, HC, and particulate matter; however, it resulted in higher NOx emissions. On average, EDI reduced NO emissions by 28.39% compared to GDI. Therefore, the optimal control strategy focused on improving performance and reducing emissions could be advantageous for the use of ethanol-blended fuels.

Isobe et al. [16] explored the effect of low-temperature heat release (LTHR) on the laminar burning velocity (LBV) of ethanol-blended gasoline surrogate fuels in a spark-ignited flex-fuel engine. The study's results indicated that higher compression ratios (CR) and exhaust gas recirculation (EGR) can enhance BTE. In a single-cylinder engine, it was established that LTHR occurred before the main combustion event, with rising temperatures positively affecting the LBV, while partial oxidants negatively impacted it. Furthermore, the findings suggested that increasing the ethanol blending ratios could lead to a higher LBV during the later stages of combustion, which may improve engine performance and contribute to decarbonization efforts.

2.2 Drawbacks and challenges with ethanol-blends in spark ignited engines

This section provides a literature review that investigates the disadvantages and challenges associated with the use of ethanol blends in SI engines, including a modest rise in NOx emissions [17]. Additionally, engine performance tends to be subpar, and specific fuel consumption may deteriorate when using ethanol blends, as noted in references [1, 2, 11, 18]. Furthermore, there is a slight increase in unregulated pollutants such as aldehydes [3], along with material compatibility concerns for higher blends exceeding E20 [4], and issues related to cold Startability, as mentioned in reference [16].

This study aimed to comprehensively evaluate ethanol blends in SI engines so that the relative significance of the positive and the negative aspects of ethanol blending in SI engines is absolutely clear. This study supports the view that the environmental benefits of ethanol-blended gasoline fuels far outweigh the seemingly adverse impact of their lower fuel economy. More ethanol-blended fuel is required to achieve a gasoline-like engine performance due to lower calorific value, leading to lower fuel economy. This impact of a lower fuel economy for ethanol-blended fuels can be mitigated due to the lower unit price of ethanol over neat gasoline.

2.3 The objectives of the study

•To examine the effects of ethanol-gasoline blends (0%, 10%, 20%) on combustion characteristics such as pressure, HRR, combustion temperature, and mass burn fraction (MBF) in a SI engine.

•To evaluate performance metrics including torque, power output, BSFC, fuel flow rate, and exhaust temperature while utilizing ethanol-blended fuel.

•To study the dependence of combustion and performance parameters, providing insights into the optimal blend ratios for enhanced engine performance utilizing ANOVA.

3. MATERIALS AND METHODS

This section presents the research methodology followed in the present work.

3.1 Test fuels

Ethanol has a nature similar to gasoline. Since both are liquids, storage and transportation are comparable. Both are easily combustible when emulsified. Ethyl alcohol is an oxygenated fuel because of its higher oxygen concentration, high H/C ratios and low molecular weight. With oxygen, it will burn completely and swiftly. These beneficial traits enhance the engine's thermal efficiency, resulting in reduced exhaust emissions. The physical and chemical properties of the gasoline and ethanol utilized in this study are presented in Table 1 [17]. These properties are explained in detail as follows.

The LHV of a fuel refers to the amount of heat produced when a specific quantity of fuel is burned at 25°C, with the combustion products maintained at 150°C, while not recovering the latent heat of vaporization of water in the reaction products. Ethanol has an LHV of 26.8 MJ/kg, which is lower than that of gasoline. As a result, to produce the same amount of work, a larger volume of ethanol must be injected, necessitating a richer stoichiometric air-fuel (A/F) ratio. This ratio is a critical factor in combustion processes, representing the optimal proportion of air to fuel for complete combustion. This leading to an increased BSFC. This effect becomes particularly critical at higher blend ratios, where the demand for fuel volume escalates significantly [18].

Table 1. Chemical and physical characteristics of ethanol and gasoline [17]

Properties	Gasoline	Ethanol
Chemical Formula	$C_nH_{(2n+2)}$ n = 4 to 12	C_2H_5OH
Density (kg/m^3)	0.742	0.79
Stoichiometric A/F Ratio	14.7:1	9:1
LHV (MJ/kg)	42.8	26.8
Auto-Ignition Temperature (°C)	~300	420
RON	95	106
Flash Point (°C at 1 atm.)	-40	13
Reid Vapor Pressure (kPa) @ 38°C)	50-90	17
Latent Heat of Vaporisation (kJ/kg)	380-500	904
Ignition Limit	0.6-8	3.5-15
Laminar Flame Speed (m/s at 25°C)	0.33	0.41
Composition (C, H and O) %wt.	86,14,0	52,13,35
Laminar Flame Speed (m/s at 25°C)	0.33	0.41

The flash point is the minimum temperature at which a liquid can emit sufficient vapor to create an ignitable mixture with air above its surface. This temperature indicates when the vapors of a volatile combustible substance can ignite in the presence of a flame. A lower flash point means that the material is more easily ignitable. Since gasoline has a lower flash point compared to ethanol, it is more readily ignited. The auto ignition temperature is the minimum temperature at which a substance can self-ignite even without the presence of a flame or spark. This temperature is very important in understanding the flammability and safety risks of different substances. Ethanol has a higher auto-ignition temperature than gasoline, which reduces the likelihood of knocking. However, this elevated auto-ignition temperature can lead to several challenges for internal combustion engines, such as decreased combustion efficiency, a potential increase in emissions, and difficulties in achieving optimal engine performance, particularly in low-temperature conditions where ignition may be less likely and stable [19]. The HoV is the amount of heat energy that is absorbed or released during the transformation of a liquid into a gas at a constant temperature. Ethanol has a higher heat of vaporization compared to gasoline, indicating that it requires more heat to vaporize. This characteristic enhances volumetric efficiency and reduces combustion temperatures; however, it also complicates the ignition and combustion processes. As a result, this can lead to challenges in attaining optimal engine performance, especially under different operating conditions [20].

Reid Vapor Pressure (RVP) is defined as the total pressure exerted by the vapor of a liquid, along with any dissolved gases or moisture, at a temperature of 37.8°C (100°F). It serves as a critical measure of the volatility of gasoline and other petroleum-derived fuels. Ethanol has a lower RVP compared to gasoline, which can lead to difficulties in engine startup under cold conditions when using ethanol-based fuels.

The octane number indicates a fuel's ability to withstand knocking during combustion in an internal combustion engine (ICE). It is assessed by comparing the fuel's knock resistance to that of reference mixtures of heptane, which is prone to knocking, and iso-octane, which resists knocking effectively. With its higher octane rating, ethanol helps minimize engine knock, allowing for a higher compression ratio. While increased compression ratios enhance thermal efficiency, modern engines often encounter difficulties using ethanol-blended fuels in cold conditions.

The laminar flame speed is a key characteristic of a combustible mixture, defined as the rate at which an unstretched laminar flame moves through a stationary mixture of unburned reactants. It is a critical parameter in combustion processes, indicating the inherent characteristic of premixed combustible mixtures. Laminar flame speed is influenced by factors such as stoichiometry, fuel structure, and thermodynamic conditions upon mixture ignition, including temperature and pressure. The laminar flame speed is a key reference quantity for characterizing and modeling combustion processes, providing valuable insights into the behavior of flames in various conditions. Higher laminar speed is attributed to faster combustion. As ethanol has a higher laminar speed, the combustion process requires less time compared to gasoline.

When blending ethanol and gasoline offline (pre-blended), it's crucial to ensure stability. Ethanol tends to move to water and lose its octane rating. Even modest amounts of water can cause phase separation, with one phase containing hydrocarbon and the other containing water and ethanol. The density differential between water and ethanol causes the phase to remain at the lower part of the fuel tank. If this is used in the engine, it can cause serious engine damage. Additionally, Ethanol's corrosive nature poses a significant issue when using higher ethanol blended gasoline in vehicles meant for gasoline operation. Ethanol may damage materials, including plastics, steel, and aluminum; hence, corrosion inhibitors are necessary to protect them. The most significant observable fault in this regard is a cold start issue with higher ethanol blended gasoline.

The research literature mentioned above suggests that increasing the ethanol content in an ethanol-gasoline blend results in reduced cold start performance in engines. This is attributed to the greater heat needed to vaporize ethanol mixtures. The elevated alcohol concentration in the blend leads to a leaner mixture, which complicates cold starting. Ethanol-blended fuels require a larger volume of fuel to achieve the same amount of air for stoichiometric conditions. The fuel system must compensate by increasing the fuel quantity; otherwise, the necessary fuel will not be available to generate the desired power. In these situations, the fuel metering systems designed for gasoline-only operation must be appropriately modified.

3.2 Experimental setup

This section furnishes the details of the experimental setup used in the present study to test the three fuels: E0, E10, and E20. Figure 1 is a schematic representation of a testing facility used to evaluate engine performance and in-combustion traits for a gasoline-powered engine. It is to be noted that the engine used during these experiments was configured as per E10 fuel.

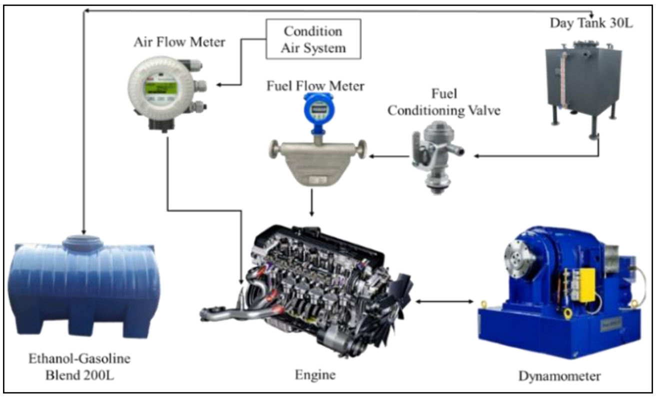

Figure 1. Experimental test setup

The engine utilized for the analysis was a multi-cylinder engine with variable speed capabilities. A concise overview of the engine is provided in Table 2. The engine was connected to a dynamometer, which generated the required load. Thermal sensors and thermocouples were employed to measure the temperatures of the engine coolant, lubricating oil, and exhaust gases throughout the testing process.

The boundary conditions for the test are given below in Table 3. A combined water-cooling system was utilized to maintain the engine's temperature. The coolant's maximum temperature was maintained at 90°C throughout each test. Additionally, a flowmeter was used to measure fuel consumption.

Table 2. Multi-cylinder engine specification

Engine Specifications	Value
Cubic Capacity	1.2 L
Engine Type	Inline
Rated Speed	6000 RPM

Table 3. Test boundary conditions

Sr. No.	Parameter	Condition
1	Air Intake Temperature	25 ± 3°C
2	Air Intake Pressure	1000 ± 5 mBar
3	Absolute Humidity	10.366 g/kg
4	Fuel Temperature	<45°C
5	Fuel Pressure	5 Bar

Table 4. Test setup

Sr. No.	Equipment	Description
1.	Fuel Flow Meter	Coriolis
2.	Air Flow Meter	ABB Sensyflow SFI-21
3.	Conditioning Air System	KS Engg., CAS06

Ethanol and gasoline mixtures were used in a separate fuel arrangement (Figure 1) to power the engine. The details of the equipment used during test are mentioned in Table 4.

Engine tests were conducted using both the regular gasoline (E0) and gasoline ethanol blends using the above-mentioned experimental configuration. The engine performance traits, such as speed, torque, fuel consumption, etc. were noted along with the combustion data such as maximum in-cylinder temperature, in-cylinder pressure, were recorded. The combustion duration and HRR were assessed through empirical techniques.

3.3 Test procedure

The engine was started and warmed up for 20–30 minutes at 1200 RPM and 20% load till the engine coolant and oil temperature reached to 80°C and 110°C, respectively. Engine testing was carried out at various speeds ranging from 1000 RPM to 6000 RPM. A test matrix shown in Table 5, gives the speed and throttle conditions along with the fuel used during the engine testing.

Table 5. Test matrix for testing

Engine (RPM)	Throttle	Fuel	Speed
6000	100%	E0, E10, E20	High Speed
4000	100%	E0, E10, E20	Medium Speed
1500	100%	E0, E10, E20	Low Speed

The dynamometer control system was employed to establish the desired engine load. Before switching to a new fuel blend, the engine was run long enough to exhaust any residual fuel from the previous test. Throughout the experiment, parameters such as engine speed (RPM), in-cylinder temperature, in-cylinder pressure, and HRR were continuously monitored. All tests were conducted under steady-state conditions, and no modifications were made to the engine hardware or calibration during the investigation. The data mentioned above was collected using a High-Speed Data Acquisition (HSDA) system, the schematic layout of which is illustrated in Figure 2.

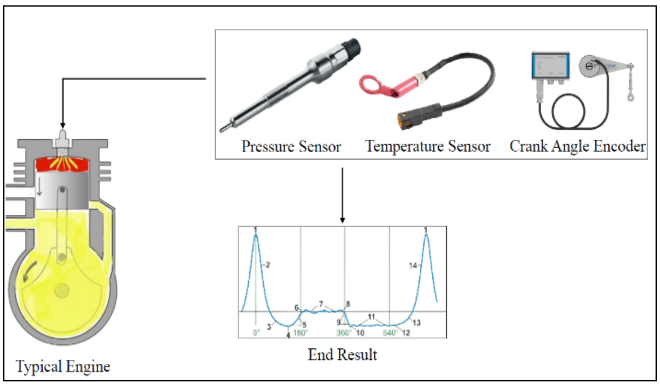

Figure 2. Schematic layout of HSDA system

The HSDA system is an essential tool for analyzing the combustion behavior of ethanol-blended fuels in internal combustion engines. By utilizing advanced sensors and instrumentation, the HSDA system gathers real-time data at various speeds, capturing key parameters such as in-cylinder pressure, temperature, and HRR. This comprehensive approach allows researchers to explore the intricacies of blended fuel combustion, offering valuable insights into performance and emission characteristics.

The HSDA system is critical to improving our knowledge of how ethanol blends affect combustion processes and the engine's performance characteristics, which will help design more efficient and ecologically friendly engine technology.

4. RESULT AND DISCUSSION

This study explored the effects of ethanol blending with pure gasoline on the performance of SI engines under varying speeds and loads. The results of the analysis of variance (ANOVA) are detailed in Table 6, which indicates significant influences of both the blend percentage and engine RPM on several in-cylinder combustion parameters, such as peak combustion pressure (P_max), peak combustion temperature (T_max), IMEP, crank angle for maximum combustion pressure (AP_max), crank angle for 10% mass fraction burned (MFB10), and crank angle for 90% mass fraction burned (MFB90). The F-values for these parameters are notably high, suggesting that the variations in the responses can primarily be linked to the independent variables, which include the fuel blends and engine speeds.

Table 6. ANOVA results (F-value and p–value) for in-cylinder combustion parameters

ANOVA	P_max		T_max	
	F-value	p-value	F-value	p-value
Blend	50.84	0.000	28.45	0.000
Speed	4974.42	0.000	4.62	0.010
ANOVA	P_max		T_max	
	F-value	p-value	F-value	p-value
Blend	125.27	0.000	1003.43	0.000
Speed	2916.67	0.000	12989.15	0.000
ANOVA	P_max		T_max	
	F-value	p-value	F-value	p-value
Blend	138.23	0.000	86.53	0.000
Speed	4756.33	0.000	869.07	0.000

The F-value, which represents the ratio of the variance explained by the model to the variance attributed to error, is a crucial indicator of the model's significance. A higher F-value signifies a substantial impact of the independent variables on the dependent variables. Moreover, all associated p-values are below 0.05, confirming statistical significance and indicating that the observed variations are unlikely to be due to random chance [21].

Figures 3-8 illustrate the variations and average changes in the engine performance parameters for all fuel blends and the three different engine speeds obtained from the experimental tests. The engine was operated at three different levels of speeds: low, medium, and high, which are represented by 1500 RPM, 4000 RPM, and 6000 RPM respectively. The combustion pressure data and HRR data collected from these tests are shown in Figures 3-8. An additional table, having comparison between each measured parameter is also provided (Table 6).

Figures 3-8 show the variations of cylinder pressure with respect to the crank angle for three different fuel blends (E0, E10, and E20) with varying engine speeds.

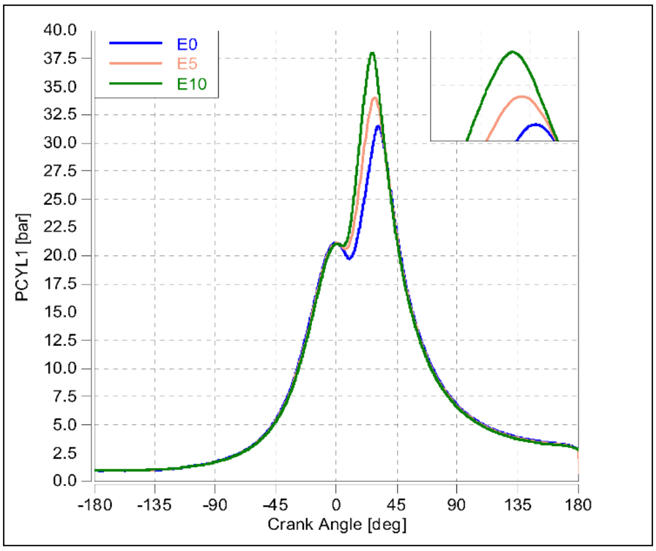

Figure 3. Combustion pressure data at FTP conditions for low engine speed

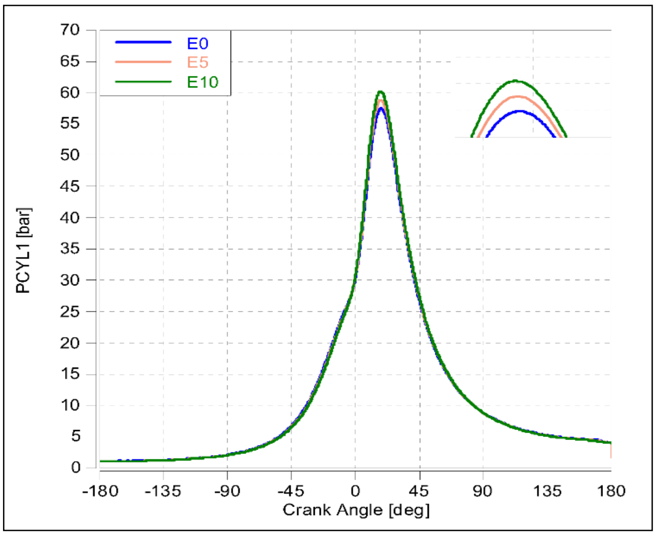

Figure 4. Combustion pressure data at FTP conditions for medium engine speed

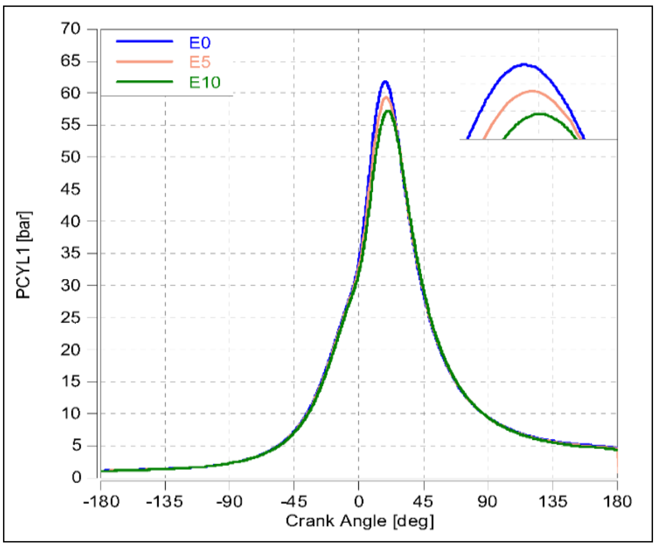

Figure 5. Combustion pressure data at FTP conditions for high engine speed

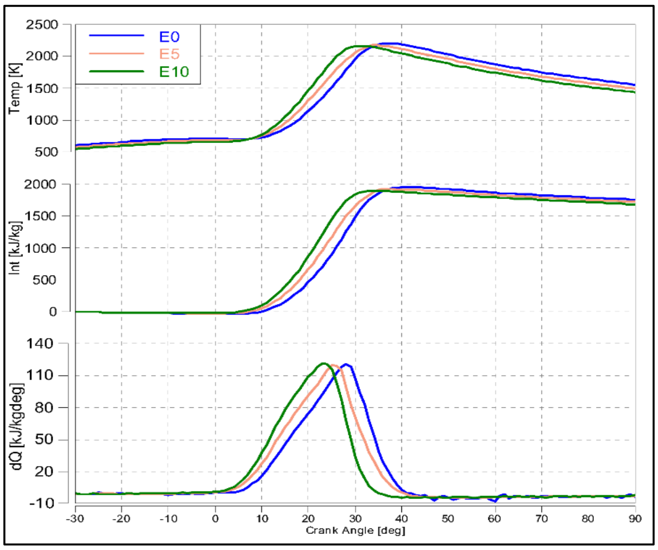

Figure 6. HRR and combustion temperature data for low engine speed

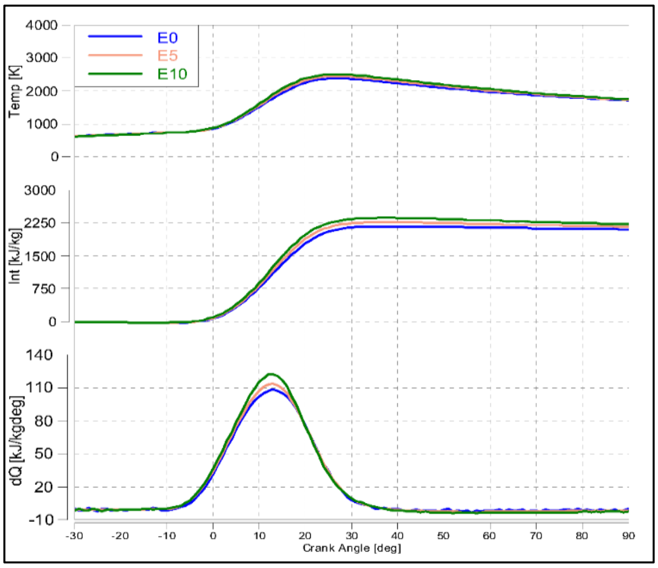

Figure 7. HRR and combustion temperature data for medium engine speed

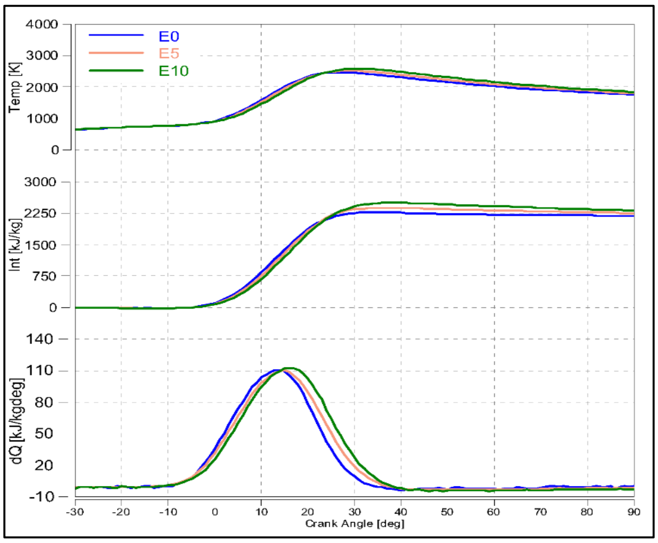

Figure 8. HRR and combustion temperature data for high engine speed

Table 7. Percentage change in various parameters w.r.t E0 for low, medium and high speed

Parameter	Low Speed		Medium Speed		High Speed	
	E10	E20	E10	E20	E10	E20
P CYLN	**21**	17.99	**4.96**	4.70	**6.12**	5.22
APMax	15.32	**17.51**	3.8	**4.9**	**5.95**	4.26
TEMP	2	**8**	**5**	4	**5**	**5**
HRR	1.1	**12.9**	12.6	**13**	**0.7**	0.4
IMEP	**8.08**	7.18	**5.8**	5.65	1.49	**1.87**
MBF 10	24.76	**25.40**	15.87	**17.5**	**34.00**	24.00
MBF 50	**19.0**	**19.0**	3.11	**3.89**	**13.6**	11.4
MBF 90	**16.5**	14.4	**1.5**	0.88	**12.1**	10.22
Comb. Dur	**8.96**	4.34	0.77	**1.79**	**9.57**	8.66

The highlighted values (bold) in Table 7 represent the highest percentage changes observed in combustion pressures and temperatures. The impact of adding ethanol to gasoline on different engine performance parameters is discussed in detail below.

4.1 Effect on in-cylinder pressure

This subsection presents an analysis of in-cylinder pressures as per the three levels of speed zones explored in this study.

Low Speeds

At lower speeds, the in-cylinder pressure (Pmax) for E10 fuel is higher than that for E0 fuel while Pmax for E10 and E20 fuel is similar. The Pmax increases when ethanol is blended. This can be mainly attributed to the higher HRR. The IMEP is also greater for E10 fuel due to the increased cylinder pressures. The combustion temperatures for E10 and E20 are lower than those for E0, which is due to the higher heat of vaporization associated with ethanol. Furthermore, the oxygen content in ethanol results in a shorter combustion duration and a quicker combustion process compared to E0 fuel. It is noteworthy that the combustion performance is better for E10 than for E20, as the base engine is specifically optimized for E10 fuel. If the engine were adjusted for E20 fuel, it could potentially achieve better performance with E20 compared to E10.

Medium Speed

At medium speed, the pattern observed is consistent with that seen at lower speeds. The peak combustion pressure (Pmax) is greater for E10 and comparable to that of E20 fuel when compared to E0 fuel. The combustion duration is shorter, while the IMEP and HRR are higher for both E10 and E20 blends in comparison to E0 fuel.

High Speed

At high speed, the trend changes and is not similar to that seen in lower and medium speeds. The Pmax is higher for E0 fuel as compared to E10 and E20 fuel. This is because firstly, ethanol takes time to evaporate and secondly, its volatility is poor as compared to gasoline. Thus, the combustion of E0 is faster as compared to E10 and E20. The combustion time at higher speeds is lower as compared to combustion time at lower and medium speeds. Hence, ethanol blended fuels are outperformed by E0 fuel at higher speeds. However, if the engine is specifically optimized for high-speed operations, the same trend as seen for lower and medium speeds can be obtained. Therefore, it is evident that, increasing the proportion of ethanol blend in the gasoline leads to higher peak cylinder pressure and improved IMEP along with faster combustion and higher HRR with lowered combustion temperatures. Figures 9 and 10 show the in-cylinder pressure

(Pmax) and crank angle at max in-cylinder pressures (APmax) for different ethanol blends.

At low and medium speeds, the increased values of peak combustion pressure (Pmax) for E10 and E20 in comparison to E0 can be attributed to the higher laminar flame speed of alcohols, which leads to quicker flame propagation during combustion [22]. At low and medium speeds, the in-cylinder combustion pressure for E10 and E20 configurations is slightly greater and faster than that of E0. High flame speed in ethanol leads to higher maximum pressure. This action accelerates combustion and increases maximum pressure levels [23].

Higher cylinder pressure results from increased oxygen availability in the chemical composition, leading to improved combustion efficiency [12]. The ease of ethanol evaporation leads to a more homogeneous charge. At higher speeds, however, owing to the increased fuel supply, the combustion of E10 and E20 slows down as engine speed increases [24]. The incorporation of ethanol into gasoline significantly influences the properties of the fuel blend. One key effect is the enhancement of the octane number and the latent heat of vaporization, which helps to postpone the chain reactions in the end gas. Another effect is a decrease in the heating value. It should be noted that these effects play opposing roles in engine performance. The initial effect is likely to dominate until the ethanol concentration reaches 10%, at which point the second effect begins to take over [25]. This decrease in heating value of fuel results in lower indicated power. As the ethanol content increases from E0 to E20, the trend for APmax (the crank angle at which maximum pressure is reached) shows a decrease, suggesting that higher ethanol levels lead to faster burn rates. This observation is supported by the fact that increased ethanol content contributes to quicker burn rates due to its higher laminar flame speed. There is a slight difference in the two Pmax peaks, which suggest that the spark was initiated much later, owing to achieve the same engine power.

4.2 Effect on HRR

This subsection discussed the effect of ethanol addition on HRR. The trends shown in Figure 11 indicate that HRR increases from low to medium speed and then remains stable from medium to high speed. The HRR is measured as heat released per crank angle and measured in kJ/kg-deg unit. The HRR clearly indicates that incorporating ethanol into gasoline results in a greater amount of heat being released, particularly noticeable when the piston reaches top dead center. Overall, the ethanol blends generate significant heat due to their high enthalpy. The oxygen-rich nature of ethanol improves combustion, which predominantly takes place near the top dead center. Figure 11 also demonstrates that using blends in engines results in greater and more effective HRR [26]. Ethanol has a latent heat of vaporization that is 2.9 times greater than that of gasoline, which renders it less effective for the evaporative atomization of the blended fuel. As a result, the combustion chamber absorbs more heat because the heat released from the mixture is diminished. This lower temperature of the fuel mixture at the time of ignition causes a slower development of the flame core. Additionally, since the ignition time stays constant, the combustion process is postponed, leading to a larger crank angle at which peak pressure occurs. This trend becomes more noticeable with an increase in mixing ratio [27].

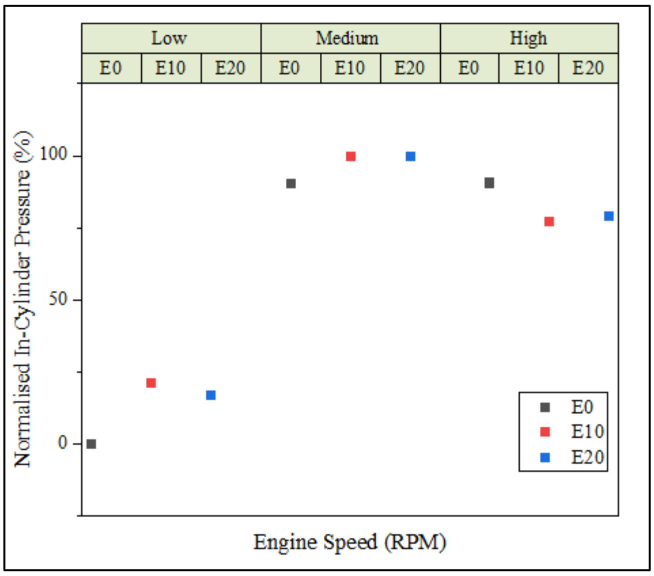

Figure 9. Speed v/s in-cylinder pressure

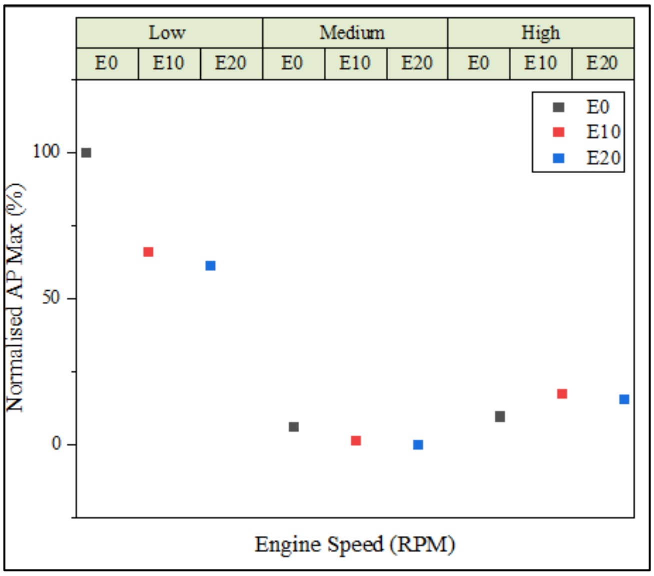

Figure 10. Speed v/s APMAX

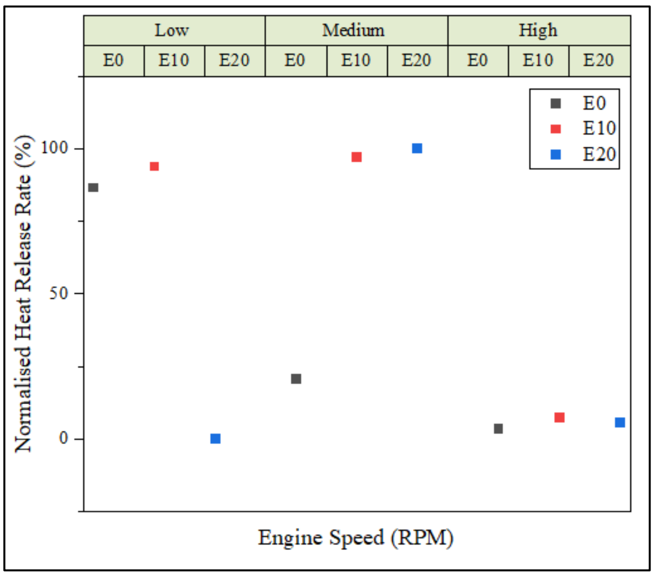

Figure 11. Speed v/s HRR

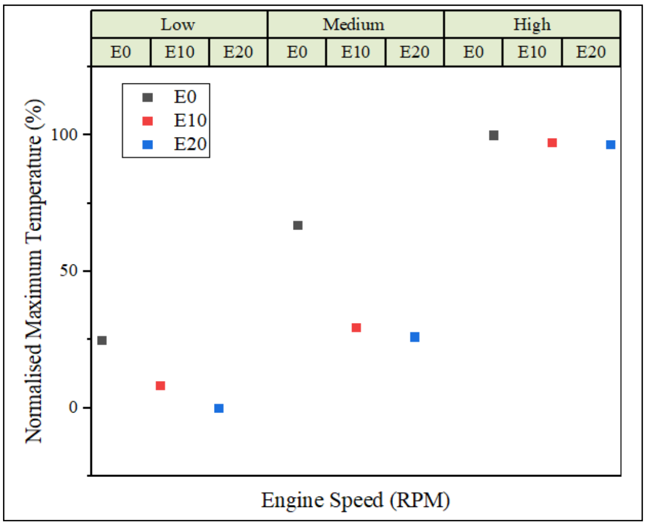

Figure 12. Speed v/s maximum temperature

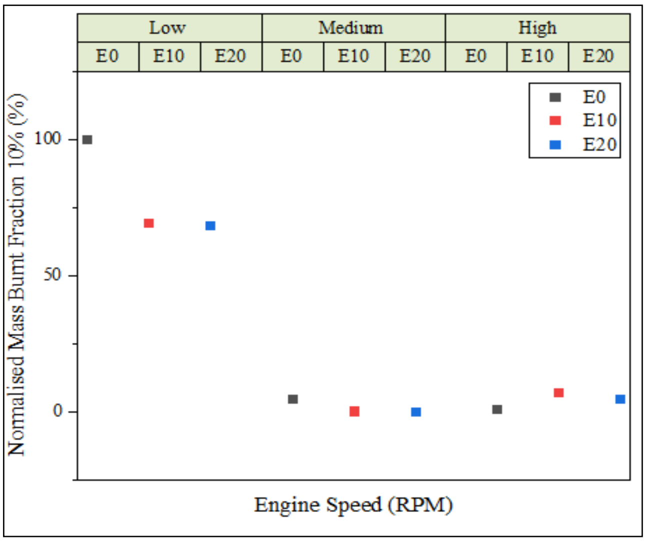

Figure 13. Crank angle (MBF10%) v/s speed

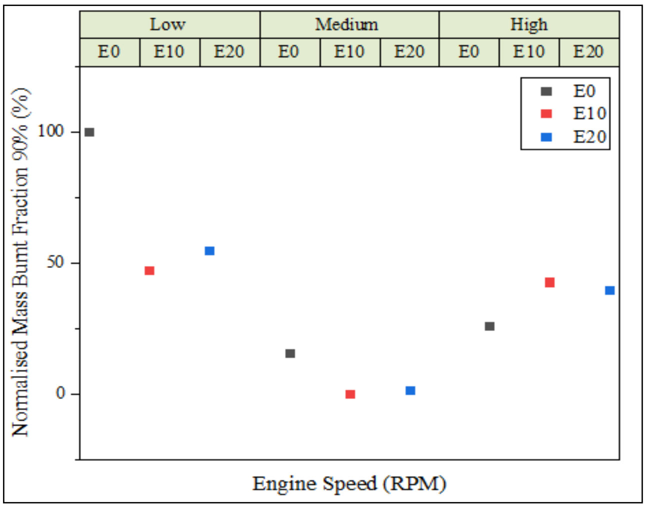

Figure 14. Crank angle (MBF 90%) v/s speed

4.3 Effect on maximum temperature

This subsection discussed the effect of ethanol addition on maximum combustion temperature. The trends shown in Figure 12 indicate that maximum temperature increases across different fuel blends (EO, E10 and E20) from low to medium speed and then remains stable from medium to high speed. Increased ethanol content leads to increased pressure and temperature in the cylinder. Ethanol's high flammability and adiabatic flame speed are responsible for this effect. The combustion is completed in a short period of time, and thus, these effects provide a small increase in torque and power, as mentioned by some researchers [22].

4.4 Effect on MBF

The effect of ethanol addition on MBF is discussed as follows.

In this study, MBF traces were used to identify the different phases of combustion. The ignition delay is defined as the angle between the beginning of fuel injection and the point at which 10% of the MBF is reached.

Meanwhile, the combustion duration (CD) is defined as the time or crank angle interval between the points where 10% and 90% of the MBF occur. The ignition delay period consists of both chemical and physical delays that occur simultaneously.

Figures 13 and 14 show a line graph with trends of MBF percentages at 10% and 90% across different speeds (Low, Medium, High) for different conditions (E0, E10, E20). MBF 10% represent the start of combustion and the crank angle for that instant. As seen in the Figures 13 and 14, there is an ignition delay while using gasoline fuel for lower speed, but the delay remains constant at medium as well as high speeds. This trend is lower in value at low speeds but increases as it moves towards medium speed, and it remains stable through high speed. This could be due to the engine's performance characteristics at low speeds, where it may be operating less efficiently. As the speed increases, the engine may operate more efficiently [28].

At low and medium engine speeds, excessive combustion duration causes the burning process to continue even when the pistons reach BDC. Thermal energy increases the in-cylinder temperature resulting in a drop in the HRR. MBF 90% represents the end of combustion. This is useful in finding out the combustion duration. As seen in the Figures 13 and 14, the combustion duration is lower at low speeds i.e. at the start of combustion but it increases as we increase the engine speed. As we move towards high speed, the combustion duration increases due to increase in fuel quantity needed for combustion. Along with this, two more characteristics of ethanol blends influence MBF. Firstly, the heat of evaporation causes an increase in ignition delay by lowering combustion temperatures. The second factor is the presence of oxygen, which facilitates combustion. Both qualities work against each other during combustion. One researcher found that using oxygenated fuel in the spray reduced pyrolysis and enhanced oxidation, resulting in shorter combustion durations [29].

These trends also can be due to the varying effects of engine speed and ethanol content in the fuel on engine performance. The engine's best characteristics can vary with speed and fuel type, reflecting the complex interplay of various factors such as fuel combustion efficiency, engine design, engine configuration, and operating conditions.

4.5 Effect on power

Power is seen to have increased as the engine speed was increased. But at medium and high speed, this difference is relatively low. As seen in the Figure 15, the power values for E0 are lower than E10 and E20 while at low speed. As the engine speed rises, the power values for the blended fuel exhibit only a slight increase. This can be explained by the lower specific heat of ethanol, which contributes to the increase in power output [11]. The high heat of vaporization of ethanol helps cool the fuel-air mixture and increases its density, resulting in a higher power output [30].

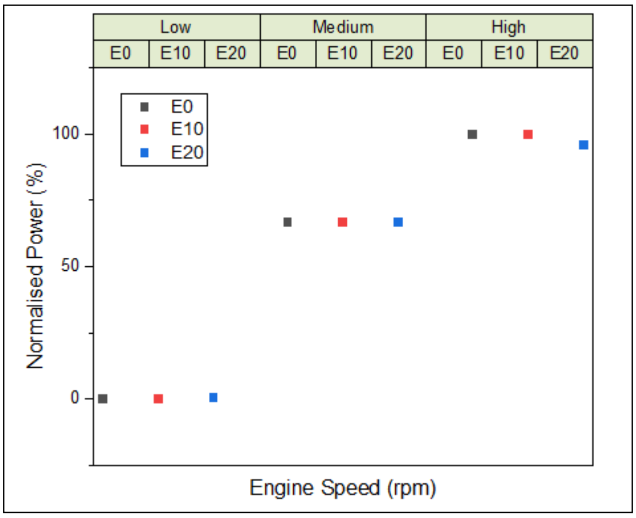

Figure 15. Speed v/s power

4.6 Effect on torque

Ethanol possesses a greater heat of vaporization compared to gasoline, which cools the fuel-air mixture and enhances its density, ultimately resulting in a higher power output. Increasing ethanol content increases engine torque [31]. Figure 16 shows that as speed increases the torque values for E10 are always higher than pure gasoline. In contrast, E20 exhibits a minor reduction in torque values when compared to gasoline. A similar observation was made in a study conducted by Yusuf and Inambao [32] who investigated the engine performance and exhaust emissions of ethanol-gasoline blends. The authors observed that, adding ethanol to fuel causes problems in starting the engine and reduces engine performance at speeds above 4000 RPM (medium speed).

4.7 Effect on fuel flow rate

The effect of ethanol blends on fuel flow rate is shown in Figure 17. The fuel flow values increase for E20 fuel as compared to E10, whereas there is a slight decrease of approximately 5-8% for E10 fuel as compared to gasoline (E0).

This finding can be explained by the fact that the blended fuel has a lower heating value per unit mass compared to gasoline. Consequently, a larger volume of fuel enters the combustion chamber for the blended fuels.

4.8 Effect on BSFC

In Figure 18, BSFC is seen to improve for E10 as compared to pure gasoline during low speed, although E10 fuel shows a decrease in BSFC during medium and high speed. E20 shows a constant increase as compared to pure gasoline and E10. As seen in Figure 18, as the ethanol proportion of the blends increases, so does the BSFC. This is because more fuel is required to generate the same amount of power as ethanol has a lower calorific value than gasoline.

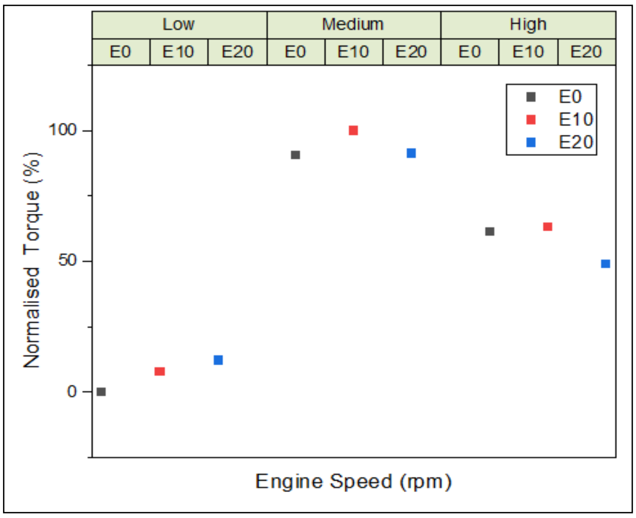

Figure 16. Speed v/s torque

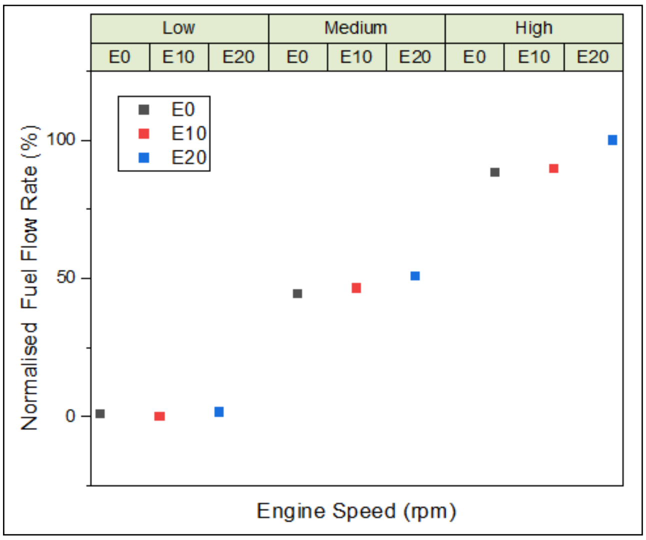

Figure 17. Speed v/s fuel flow rate

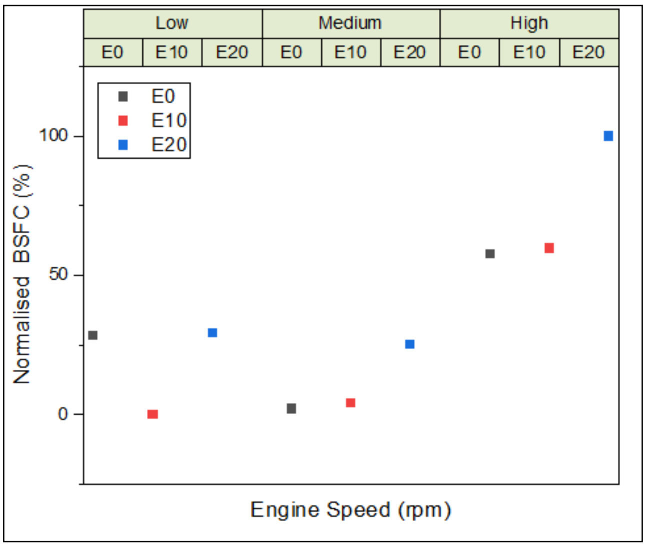

Figure 18. Speed v/s BSFC

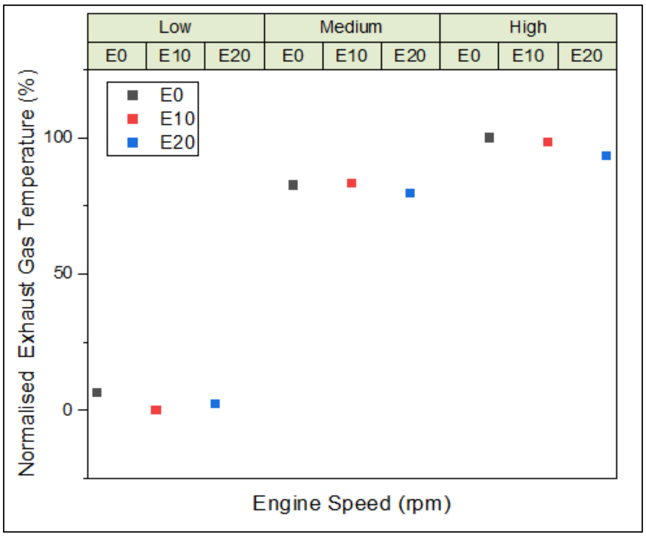

Figure 19. Speed v/s exhaust temperature

4.9 Effect on exhaust temperature

In Figure 19, the exhaust temperatures are seen to decrease for ethanol blends. Ethanol blends show the lowest temperature during low speed, whereas, as the speed increases, the difference between gasoline and blends is close to 5-10%. This can be attributed to ethanol combustion, which produces more exhaust gas per heating value input, leading to increased heat capacity and exhaust temperatures [10].

4.10 Comparisons with existing literature

To enhance understanding and facilitate comparisons, the outcome of this study is compared with contemporary studies and presented as follows.

In the first comparison, Mohammed et al. [33] investigated the effects of ethanol-gasoline blends (from 10% to 40%) on brake power, thermal efficiency, volumetric efficiency, and BSFC in a single-cylinder, naturally aspirated engine at various speeds. The results showed a 14.67% increase in brake power at 1500 RPM, while BSFC dropped by 17.21% at 2500 RPM for the E40 blend compared to pure gasoline. Additionally, BTE improved by 31.12%. Although this study used a different engine type, testing cycle, and ethanol blending ratio than that of Mohammed et al. [33], both studies found an increase in power output and a reduction in BSFC. However, while Mohammed et al. [33] reported an increase in torque, the present study observed a decline in torque for E10 and E20 blends.

In the second comparison, Ramadhas et al. [34] utilized a four-cylinder SI engine to evaluate emissions from ethanol-gasoline blends, specifically E5, E10, and E20. The findings indicated a 2.5% increase in torque for the E20 blend at 3000 RPM. Furthermore, brake-specific energy consumption decreased by 25%, 10%, and 15% for the E5, E10, and E20 blends, respectively, under low-load conditions. While the engine type and ethanol blending percentages in this study differ from those in study [34], the latter reported an increase in torque, whereas the present study observed a decrease in torque with higher ethanol content.

In the third comparison, Ye et al. [35] studied the influence of 10%, 20%, and 30% ethanol blends on a fuel-injected gasoline engine. The brake power was decreased by 2.34%, 5.63 and 13.615% for the respective blends (E10-E30) compared to pure gasoline. The BSFC was increased by 10%, 18%, and 43% for E10, E20, and E30, respectively, at higher load. The exhaust gas temperature was decreased by 1.20%, 3.60%, and 8.40% for 10-30 blends percentages, respectively, at 3000 RPM. An increase in the brake power, BSFC and a decrease in the exhaust gas temperature were reported in the investigation performed by Ye et al. [35] in this current study as well.

In the fourth comparison, Najafi et al. [36] performed a study on a SI engine using various ethanol blend fractions, including E5, E7.5, E10, E12.5, and E15. The findings revealed a 3.92% increase in torque for E15 at 3500 RPM, while BSFC rose by 2.8% for E5 at the same speed. Additionally, brake power increased by 16.21% for E15 compared to E5 at 4000 RPM. The study noted an increase in torque at medium speeds, whereas the current study observed an increase in torque at low speeds. The trend in BSFC was consistent across both studies.

In the fifth comparison, Balki et al. [37] examined the impact of ethanol at full throttle in a spark ignition engine. They observed a 3.7% increase in torque when using ethanol compared to gasoline, while brake specific fuel consumption (BSFC) rose by 58%. The trend of increasing BSFC was noted to correlate with the percentage of ethanol blend in both studies. The authors indicated that torque improved with higher blend percentages at low speeds, whereas the current study found an increase in torque at medium speeds.

5. CONCLUSION

This study presented an analysis of the impact of ethanol-gasoline blends (E0, E10, E20) on the performance of spark ignition engines. The main findings are summarized as follows:

•The ANOVA results indicate that both ethanol blends and engine speed significantly affect the in-cylinder combustion parameters.

•According to this investigation, both the E10 and E20 variants show somewhat higher and faster in-cylinder gas pressure than E0 at low and medium speeds.

•A characteristic pattern may be seen in the HRR, which rises from low to medium speed before stabilizing from medium to high speed. This points to a complex interaction between engine speed and ethanol content-influenced combustion properties.

•There is a complex link between ignition delay and engine speed, beginning with a lower value at low speeds, increasing towards medium speeds, and stabilizing at high speeds.

•Pmax, IMEP, and HRR were higher for E10 and E20 compared to E0 for low and medium speeds, whereas the trend was reversed at higher speeds.

•Burn duration was reduced for E10 and E20 compared to E0 for low and medium speeds. However, the trend was reversed at higher speeds.

•Power and torque levels were found to be higher with E10 and E20 compared to E0 at medium and high speeds, whereas a reverse trend was seen at lower speeds. The greater heat of vaporization of ethanol aids in cooling the fuel-air mixture, which increases its density and, in turn, enhances power output.

•At all operating speeds, brake specific fuel consumption (BSFC) worsens because the blended fuel has a lower calorific value.

•Higher blends of ethanol reduce exhaust temperatures, with low speed resulting in the lowest temperatures. The temperature differential between gasoline and blends decreases with increasing engine speed, highlighting the cooling impact of ethanol mixes on combustion.

In conclusion, this study thoroughly examines multiple variables that offer important new information on the intricate relationships between engine speed, combustion characteristics, and ethanol-gasoline mixtures. The results of this study offer a thorough grasp of the possible advantages and difficulties of using ethanol-blended fuels in spark ignition engines, setting the stage for further investigation and improvement in the hunt for environmentally friendly and effective combustion processes. In the future, more investigation may focus on maximizing mix ratios to reduce emissions without sacrificing engine performance.

6. FUTURE SCOPE AND RECOMMENDATIONS

The future scope of the present study may include the following research objectives and recommendations.

•To analyze emissions produced by various ethanol blends, aiming to understand their environmental impact and compliance with regulatory standards in automotive applications. The use of a suitable after-treatment system can be explored.

•To examine the effects of ethanol-gasoline blends on engine performance, an optimized calibration was conducted by adjusting parameters like the air/fuel ratio, compression ratio, injection timing, and spark ignition timing.

•To assess the impact of higher ethanol blends (30% and above) on combustion characteristics and performance metrics, with the aim of determining their potential for improving engine efficiency.

•To optimize engine calibration techniques and combustion parameters to effectively reduce nitrogen oxide (NOx) emissions during operation. The effectiveness of EGR can be explored.

•To assess the compatibility of various materials used in engine components with ethanol-blended fuels to ensure durability and performance. Material compatibility studies can be performed for metallic and non-metallic components in contact with fuel.

•To perform an extensive comparison of unregulated emissions, including aldehydes and particulate matter, and assess their environmental effects and regulatory compliance.

•To explore both engine calibration adjustments and physical modifications to enhance cold-start performance, ensuring reliable operation in low-temperature conditions. The use of glow plugs can be explored in cold region operations.

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