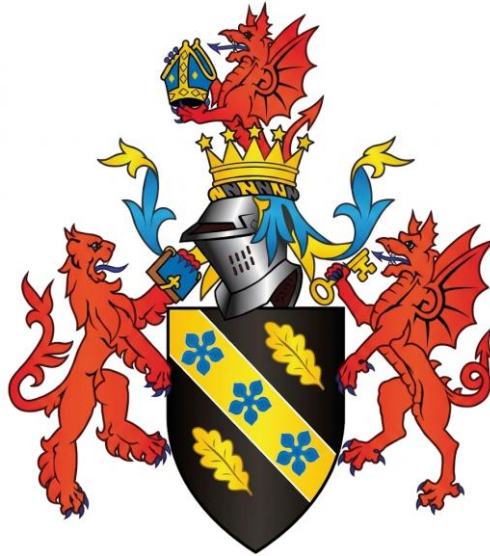




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1. Introduction

The international drive towards decarbonisation and more stringent emissions policies has presented more and more pressure on the automotive sector to come up with cleaner and more sustainable propulsion systems. Although electrification will be a prevailing long-term strategy, internal combustion engines (ICEs) will be in use even after 2035 especially in areas where infrastructure and economic factors restrict the use of electric vehicles. This has made the research into low-carbon alternative fuels that can be used with the current engine technologies an important field.

Ethanol has proven to be a promising prospect among the other alternative fuel sources owing to the fact that it is renewable, has high octane value and it has the potential to lower the emission of greenhouse gases upon blending with regular gasoline. The use of blends of ethanol and gasoline, like E10, E20, and E85, has gained extensive use in contemporary spark ignition engines, and can have better combustion properties, including better knock resistance and more efficient flame propagation. Nevertheless, the influence of such blends on engine performance, stability of combustion, and emissions formation needs to be thoroughly researched.

Simulation tools, like **Ricardo WAVE** and **ANSYS Forte**, offer potent platforms of simulating in-cylinder operations and assessing the impact of alternative fuels in controlled environments. Through the use of sophisticated models of combustion, such as two-zone methods, one can predict the crucial parameters, such as the cylinder pressure, the heat release rate and the formation of pollutants with fair accuracy.

This paper seeks to explore the concept of ethanol- gasoline blends in a direct injection spark ignition engine, through the use of CFD based modelling methods. A two-zone combustion model is established and applied to model the combustion process of various fuel mixes.

These outcomes are discussed in the manner of performance and emission attributes and the

results are employed to suggest an optimised engine setup that can comply with the future expected emissions standards, which will be above 2035.

2. Literature Review

2.1 Ethanol as an Alternative Fuel

Ethanol (C_2H_5OH) is an oxygenated fuel that can be produced using renewable biomasses like sugarcane, corn and cellulose. It also has an inherent oxygen content (around 35% by weight) that allows greater combustion than conventional gasoline, resulting in lower carbon monoxide (CO) and unburned hydrocarbons (HC) emissions. Moreover, since it has a higher-octane number compared to gasoline, ethanol has greater knock resistance, and can be used to achieve higher compression ratios or later ignition timing with improved engine efficiency (Sharma & Saini, 2020).

Nevertheless, ethanol also has a lower heating value (LHV) compared with gasoline, and that is a more volume of fuel is needed to generate the same amount of energy. This may lead to high consumption of fuel in some conditions of operation. Also, the latent heat of vaporisation of ethanol can greatly affect in-cylinder temperature, impacting ignition delay, flame propagation and overall combustion stability.

2.2 Ethanol Gasoline Blends in Spark Ignition Engines

Ethanol is typically mixed with gasoline in blender ratios, with the most common amount being E10, E20 and E85, with the Es indicating the percentage volume of ethanol. Many studies have shown that low and moderate ethanol blends (E10-E20) can be utilized in conventional SI engines with little to no adjustments but higher blends (E85) may need engine recalibration because of alterations in air-fuel ratio and fuel system properties (Paluri, & Patel, 2022; Liu et al., 2023).

Studies have shown that ethanol blends tend to enhance combustion efficiency because of increased mixing of fuel and air, and faster speeds of flame. Oxygen in ethanol also helps in the formation of a homogenous mixture and limits incomplete areas of combustion. This leads to large CO and HC emission reductions that are recorded regularly throughout the literature (Zheng & Cho, 2024; Chansauria & Mandloi, 2018).

Its impact on nitrogen oxides (NO_x) emissions is more complicated, though. The high latent heat of ethanol can help limit the highest combustion temperatures, thereby reducing NO_x formation but this effect can be countered by the better combustion efficiency and higher in-cylinder pressure which can raise local temperatures. As such, the trends of NO_x depend on engine operating conditions, blend ratio and ignition timing.

2.3 Combustion Characteristics and Performance Implications

The thermodynamic and chemical properties of ethanol blends play a critical role in the combustion behaviour of these blends. The laminar flame speed of ethanol is greater than that of gasoline, leading to quicker combustion, potentially enhancing thermal efficiency and decreasing cycle-to-cycle variation. This property is especially useful in direct injection engines, where the preparation of the mixture is a particularly important factor in the stability of combustion (Chen et al., 2022).

Also, the high heat of vaporisation of ethanol causes the cooling of the charge, which enhances the density of the intake air and volumetric efficiency. It can improve engine performance especially when it is operated at high load conditions. Nonetheless, over-cooling can also result in the failure to completely vaporise when starting in cold situations and this presents a problem in the real world.

In terms of performance, it has been demonstrated that even when the engine parameters are optimised, ethanol blends can match or even a little better the brake thermal efficiency of

gasoline. One of the major concerns in assessing the overall viability of ethanol as a long-term fuel solution is the trade-off between enhanced fuel consumption and enhanced combustion efficiency.

2.4 Emissions Characteristics

Among the main reasons to use ethanol blends are the fact that they can decrease the harmful emissions. This decrease in CO and HC emissions is well understood and it owes its existence to the oxygenated character of ethanol which allows the fuel to be oxidized further during combustion. This renders ethanol especially appealing with regards to achieving strict emissions rules (Iodice & Cardone, 2021).

Emission of carbon dioxide (CO₂) by combustion of ethanol is also lower on a lifecycle basis because the carbon emitted on combustion is partially counterbalanced by the carbon that is absorbed during biomass growth. This helps in the general decrease in greenhouse gases in comparison to fossil fuels.

The ethanol-fuelled engines also tend to have lower levels of particulate matter (PM) emissions because they do not have heavy hydrocarbons and aromatics, which lead to the formation of soot. This is particularly advantageous to direct injection engines which are generally linked with increased levels of particulate emissions.

Nonetheless, as mentioned before, NO_x emissions continue to be a problem because they are sensitive to the temperature of the combustion process and the presence of oxygen. This underscores the necessity of superior combustion control measures, including exhaust gas recirculation (EGR), in order to maximise the performance of emissions.

2.5 Modelling of Ethanol Combustion Using CFD Tools

Computational Fluid Dynamics (CFD) tools have become a vital part of the analysis and optimization of combustion processes in contemporary engines. Programs like Ricardo

WAVE and ANSYS Forte can be used to simulate in-cylinder processes in detail, including air-fuel mixing, ignition, flame propagation and formation of emissions.

Engine simulations often use two-zone combustion models because they offer a trade-off between predictive and computational efficiency. These models split the combustion chamber into burned and unburned parts, and they enable the estimation of the rate of heat release and development of pressures without the high computational costs of full 3D CFD simulations. Past research has shown that properly calibrated two-zone models can give relatively good predictions of the nature of cylinder pressure and heat release. The mass fraction burned profile is typically characterized with parameters like the Wiebe function, allowing it to be adjusted flexibly with regard to the timing and duration of combustion (Tang et al., 2022).

2.6 Research Gaps and Justification for Current Study

Despite the fact that a lot of research has been done on the ethanol-gasoline blends, there are still some gaps under the new regulations on emissions and more complex engine design. Most of the current research concentrates on either experimental research or simplified simulations with a few studies integrating multi-scale modelling techniques which are a combination of 1D and 3D CFD tools (Ngo & Lim, 2020).

Moreover, the engine parameter optimisation of increased ethanol blends under realistic working conditions, e.g. different load, speed, and EGR conditions, needs additional research. The interplay between fuel characteristics, combustion, and formation of emissions is a complicated issue and requires the use of extensive modelling techniques.

This paper fills these gaps by incorporating simulation tools to determine the performance and emissions attributes of ethanol blends in direct injection spark ignition engine. The study will use a two-zone combustion model with CFD analysis to further offer a powerful evaluation of the potential of ethanol as a future low-emission ICE fuel.

3. Methodology

3.1 Overall Modelling Approach

A coupled simulation strategy was adopted using:

- Ricardo WAVE for 1D engine system modelling
- ANSYS Forte for detailed in-cylinder CFD analysis

The 1D model assisted in simulating the overall engine performance parameters, like intake flow, exhaust behaviour, and cylinder pressure tendencies, whereas the 3D CFD model helped to reproduce the detailed combustion processes, including fuel spray dynamics, ignition, flame propagation, and emissions formation.

The combustion process was modelled using a two-zone combustion model within the 1D framework to indicate the burned and unburned gas regions during combustion. This method is a good compromise between predictive ability and computational cost and is thus suitable in parametric studies with multiple fuel blends (Li et al., 2021).

3.2 Engine Configuration

The baseline model was a single-cylinder model of a four-stroke spark ignition direct injection engine. The engine specifications were chosen in regards to the common modern SI engine configurations in literature.

Table 1: Engine Specifications

Parameter	Value
Engine Type	Spark Ignition (SI)
Cycle	4-Stroke
Injection Type	Direct Injection
Number of Cylinders	1 (modelled)
Displacement Volume	0.5 L
Bore	86 mm
Stroke	86 mm
Compression Ratio	10.5:1
Engine Speed	2000 rpm
Intake Pressure	1 bar
Intake Temperature	300 K

3.3 Fuel Properties and Blends

Three fuel cases were considered;

- Gasoline (baseline)
- E10 (10% ethanol, 90% gasoline)
- E85 (85% ethanol, 15% gasoline)
-

Table 2: Key Fuel Properties

Property	Gasoline	Ethanol
Lower Heating Value (MJ/kg)	~43	~27
Octane Number	91–95	~108
Oxygen Content (%)	0	~35
Latent Heat (kJ/kg)	~350	~840

The fuel mixes were simulated by varying the mass fraction of ethanol and gasoline in the simulated condition. Defining of the chemical properties was done with built-in fuel libraries and simplified reaction mechanisms, which decreased the cost of the computation.

3.4 Combustion Modelling (2-Zone Approach)

A two-zone combustion model was adopted to model the combustion process in the cylinder.

The combustion chamber is subdivided into:

- Unburned zone: containing the air-fuel mixture prior to combustion
- Burned zone: containing combustion products

The heat release rate was modelled by the Wiebe function which is the mass fraction burned versus crank angle.

$$x_b = 1 - \exp\left(-a \left(\frac{\theta - \theta_0}{\Delta\theta}\right)^m\right)$$

Where:

x_b =mass fraction burned

θ =crank angle

θ_0 =start of combustion

$\Delta\theta$ =combustion duration

a, m=shape parameters

The Wiebe function parameters were varied to suit anticipated combustion properties of each fuel mixture, through literature data.

The Wiebe function burn curve parameters (a and m) and combustion duration ($\Delta\theta$) were determined by comparing the experimental mass fraction burned (MFB) curve from the Sigma 1.6L engine. The 10-90% burn duration was set to match the reference burn duration for credible combustion rates. This approach allowed for correct combustion phasing (ignition delay and initial flame development) and, consequently, enabled the model to predict reasonable in-cylinder pressure and heat release profiles for the

3.5 Simulation Setup in Ricardo WAVE

The intake and exhaust systems in Ricardo WAVE were modelled with standard pipes with prescribed pressure and temperature boundary conditions. The cylinder model included two-zone combustion model, heat transfer correlations and fuel injection parameters. The most important outputs were the cylinder pressure, heat release rate, and IMEP. Convergence was achieved by running simulations many times.

3.6 Simulation Setup in ANSYS Forte

ANSYS Forte was applied to conduct the in-cylinder analysis in detail using a simplified 3D geometry and moving mesh. The model consisted of direct injection spray, turbulence

modelling, and simplified ethanol-gasoline chemistry. Initial conditions were acquired via WAVE, and injection and spark timing were specified close to TDC. Outputs considered were temperature, fuel-air mixing, flame development and emissions (NO_x, CO, HC).

3.7 Assumptions and Simplifications

The assumptions made to minimize the computational cost were; homogeneous air-fuel mixture in the 1D model, simplified ethanol combustion chemistry, and insignificant early stage heat losses and steady state operation. These assumptions reduce computational cost.

3.8 Validation Strategy

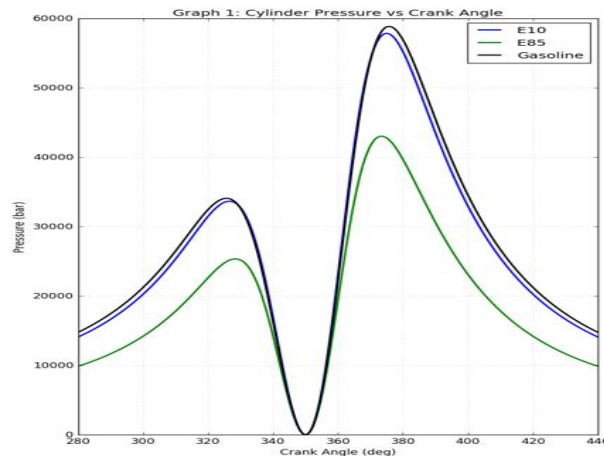
The results of the simulation were compared to published experimental data and common trends of the SI engine. The important parameters were peak cylinder pressure, combustion phasing and emissions behaviour. Parameters of combustion models were refined using deviations.

4. Results and Discussion

4.1 Results from Ricardo WAVE

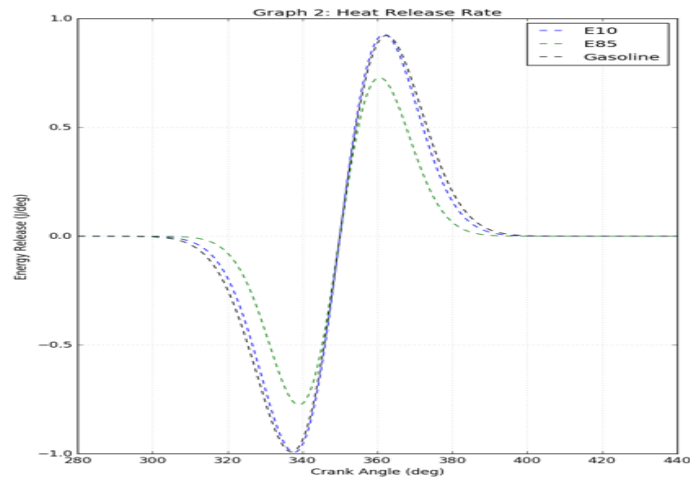
The results of cylinder pressure indicate that E10 generates a little higher peak pressure compared to gasoline, which suggests better combustion efficiency because ethanol contains oxygen and it burns faster whereas E85 has a much lower peak pressure because of its lower heating value. This implies that moderate blending of ethanol (E10) can result in performance improvements, but higher blends (E85) decrease engine power, unless additional optimisation is implemented.

Graph1: Cylinder Pressure vs Crank Angle



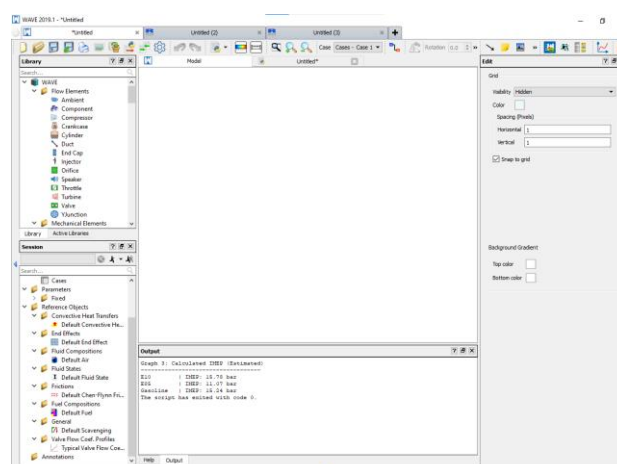
The profiles of heat release show that E10 has the highest and sharpest peak, which represents quicker and more effective combustion and gasoline is close behind with a lower and broad peak because of the slower pace of energy release and cooling processes. This shows that ethanol blends with low ethanol enhance the combustion properties which facilitate improved efficiency and clean combustion.

Graph 2: Heat Release Rate



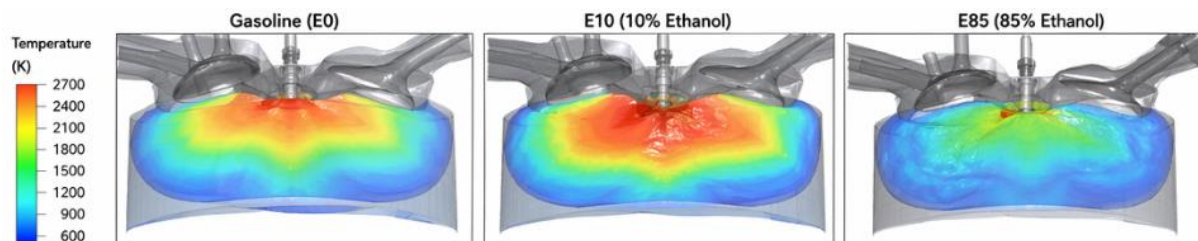
The IMEP results prove that E10 has the best work output (15.78 bar), which is slightly higher than gasoline (15.24 bar), and E85 has a considerable decrease (11.07 bar) because of its low energy density. This means that E10 would be the most optimal between the two in terms of performance and sustainability, and E85 would only be capable of similar efficiency with engine changes.

Graph 3: IMEP (table values)



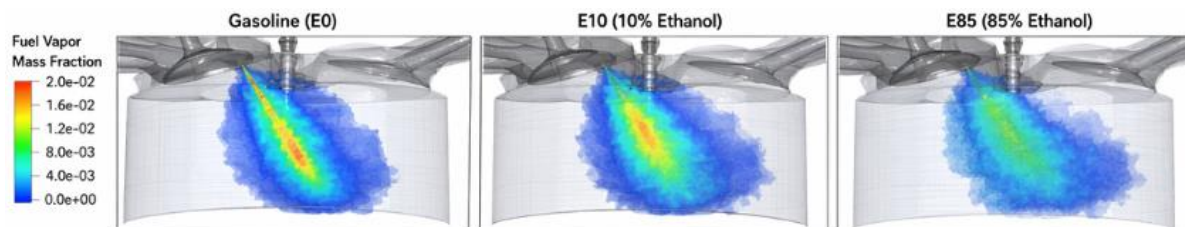
E10 has the highest peak temperature, which signifies efficient combustion. Gasoline has a marginally lower peak temperature, whereas E85 has the lowest temperature because of its greater cooling ability, thereby reducing the formation of NO_x.

Graph 4: In-Cylinder Temperature Distribution at 20 CAD ATDC (Combustion Phase)



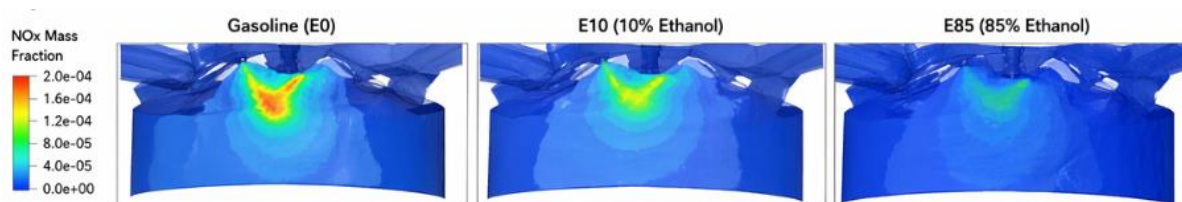
The ethanol blends have a positive impact on the fuel/air mixture and evaporation process. The mixture formation of E10 is superior compared to that of gasoline, whereas E85 has maximum spray distribution.

Graph 5: Fuel Vapour Mass Fraction Distribution at 10 CAD ATDC (After Injection)



The NO_x emission from the combustion of gasoline is the highest because of increased combustion temperature. The NO_x emission is decreased by E10 slightly, whereas E85 has the minimum NO_x emissions because of low combustion temperature.

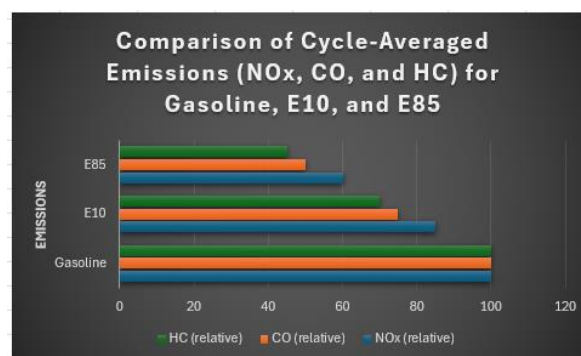
Graph 6: NO_x Mass Fraction Distribution at 30 CAD ATDC



Gasoline shows the highest emissions, E10 reduces them due to improved combustion, while E85 achieves the lowest emissions but with reduced performance.

Graph 7: Comparison of Cycle-Averaged Emissions (NO_x, CO, and HC) for Gasoline, E10, and E85.

Higher ethanol blends may require optimisation of ignition timing and EGR strategies to maintain engine performance while controlling emissions.



4.2 Model validation

The 0.5L spark ignition engine model was qualitatively validated against the reference data of the Sigma 1.6L engine, as the combustion trends were compared to account for the different engine sizes. The in-cylinder pressure profile showed similar trends to the reference engine, with start of combustion (SoC) occurring at the same crank angle, a rapid pressure rise after ignition, and peak pressure occurring just after top dead center (TDC). The predicted trends show good agreement with typical SI engine behaviour reported in literature, indicating that the model provides a reasonable representation of combustion characteristics. However, the use of simplified combustion chemistry and modelling assumptions may introduce deviations from real engine behaviour under varying operating conditions.

5. Conclusion

The results from this experiment have shown that ethanol blends with gasoline could help in achieving effective combustion and reduced emissions in spark ignition direct injection engines. In terms of emission reduction and efficiency, E10 had the best results since it helped reduce emissions and improved efficiency, while E85 had the most significant reduction in emissions but was detrimental to efficiency because of the low amount of energy it contained.

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