HYDROGEN ENGINE EFFICIENCY AND EMISSIONS SIMULATIONS

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ABSTRACT
This research delves into the intricate relationship between four pivotal engine parameters — compression ratio, Lambda(air-fuel ratio), engine load, and engine speed — and their combined impact on the efficiency and NOx emissions of hydrogen-fuelled internal combustion engines. As the global quest for sustainability and environmentally friendly energy solutions intensifies, hydrogen has emerged as a promising alternative fuel due to its affluence and clean combustion properties. Ricardo WAVE is used to simulate the hydrogen internal combustion engine by modifying the existing inline 3-cylinder engine. Nevertheless, unlocking the full potential of hydrogen engines necessitates a profound understanding of how these parameters influence engine performance and emissions. This study employs a synergistic approach, combining simulation and experimental analysis to investigate the effect of these parameters on hydrogen IC engines. An air-fuel ratio of 55(Lambda 1.67) and a compression ratio of 14.1 would be suitable for a hydrogen internal engine under lean burn conditions The findings contribute valuable insights into the design and operation of hydrogen engines, thereby facilitating their widespread adoption as a cleaner alternative to conventional fossil fuel engines.
Keywords : Compression ratio; Lambda; hydrogen engine; Ricardo WAVE

INTRODUCTION :
The increasing concern about environmental changes and greenhouse gases leads to intense interest in alternative fuels and cleaner energy sources. Hydrogen is a clean, sustainable and renewable energy carrier. Which has been identified as a promising alternative to fossil fuels for internal combustion engines. Despite this, the development of hydrogen engines faces a handful of challenges, including optimizing engine performance and reducing emissions.
In recent years, the need to combat the environmental changes and reduce greenhouse gas emissions has sparked a surge in the stalking of sustainable energy solutions. Among the various alternatives, hydrogen has gained attention due to its clean-burning properties. Hydrogen internal combustion engines can significantly reduce emissions, particularly carbon dioxide (CO_2). (G. D. Brewer, 1978)
However, to fully utilize the potential of hydrogen engines, it is essential to gain an understanding of how operating parameters impact their performance and emissions. By using iterative methods and optimizing these engines, the full potential can be unlocked, and significant steps can be taken towards a more sustainable energy future.
Hydrogen is a chemical element donated by the symbol ‘H’ and atomic number 1. Is most simplest and most abundant element in the universe, which consists of a single proton and an electron. Hydrogen is a colourless, odourless, and tasteless, yet highly flammable element. Hydrogen is a diatomic molecule under standard conditions. (Reid, 1987) It has extremely high boiling and low melting points, which makes it a gas at room temperature.
As the lightest element in the periodic table, hydrogen exhibits well-defined physical properties that set it apart from the other elements. (Reid, 1987) Its exceptionally low atomic mass contributes to its high buoyancy and high diffusivity. Its low molecular weight and high reactivity make hydrogen a base element for several uses, including chemical synthesis, aerospace, and energy storage applications. Hydrogen for IC engines can be produced by using different methods, which include electrolysis, alkaline electrolysis, steam methane reforming(SMR), proton exchange

membrane(PEM) electrolysis, and biological and thermochemical processes. (Dincer Akal et al., 2020)
Hydrogen IC engines can use various types of hydrogens, such as compressed hydrogen(CH2), Liquid Hydrogen(LH2), hydrogen gas(HG), and hydrogen-rich gas(HRG). Compressed hydrogen is the most commonly used in hydrogen IC engines. Usually, the compressed hydrogen is stored in high-pressure tanks, typically compressed to 350-700 bar. Liquid hydrogen is another alternative which can be used in hydrogen IC engines. Liquid hydrogen is stored in cryogenic tanks and requires a complex cooling system to maintain its liquid state. (Sage et al., 2023)
Hydrogen gas is a type of hydrogen which is not compressed or liquified. It is usually used in low-pressure applications, such as fuel cells or internal combustion engines with low compression ratios. On the other hand, hydrogen-rich gas is a mixture of methane, propane, or natural gas. It can be used in IC engines, but its performance and emissions may vary depending on the type of gas mixed with hydrogen.
The selection of hydrogen for the hydrogen IC engine plays a crucial role in ensuring engine performance, efficiency, and emissions. The International Organisation of Standardization (ISO) recommends ISO 14687(purity level of 99.97% for compressed hydrogen) and ISO 14687-2(purity level of 99.995% for liquid hydrogen).(Dincer Akal et al., 2020)
Hydrogen is an emerging opportunity as a clean energy carrier, as a multifaced element with a wide range of industrial applications which help to reduce carbon emissions. Hydrogen is mainly used in fuel cells, energy storage, and transportation. (Stępień, 2021) In fuel cells hydrogen fuel cells convert hydrogen into electricity, producing only water as a byproduct. The fuel cells are used in various streams like vehicles, portable power and stationary power generation. Hydrogen can be used to store excess renewable energy, and upon the requirement, it can be converted back into electricity. Energy storage can advance to have the potential to balance supply and demand in the electric grid, which ensures stability in energy production. (Dincer Akal et al., 2020) (Mogi et al., 2022)
Various applications like buses, cars, and even aircraft, are using hydrogen as the fuel which offers a zero-emission alternative to fossil fuels. The greenhouse gases are mainly produced by the transportation sector. Significantly, hydrogen can reduce the greenhouse gas emissions. As the world is marching towards a low-carbon energy future, hydrogen is likely to play a crucial role in reducing greenhouse gas emissions and mitigating climate change. (Sage et al., 2023) (Dincer Akal et al., 2020)
Hydrogen-fuel internal combustion engines offer various advantages when compared to traditional internal combustion engines. Hydrogen can play a vital role in climate change and reduce emissions. Hydrogen is rich and can be produced from various renewable sources, potentially which can ensure a limitless supply. (Dincer Akal et al., 2020)
Hydrogen internal combustion engines could be less expensive compared to hydrogen fuel cell vehicles and battery electric vehicles, due to the similar manufacturing process as traditional gasoline and diesel engines. Moreover, hydrogen vehicles can achieve more ranges compared to traditional combustion engines because of their hydrogen chemical properties. Hydrogen Refuelling can be done similarly to LPG.(Vorst, and Finegold, 1975)
Hydrogen combustion engines are similar in operating and maintenance to traditional engines, which can offer enormous advantages in terms of integration and familiarity. Hydrogen IC engines can ease the transition for both manufacturers and consumers habitual to conventional technology. Due to the similarity of working and design can also allow to use of the existing supply chains for the production of the hydrogen IC engines and reducing the cost associated with the transition of the new technology.
Nevertheless, the advantages of hydrogen in internal combustion vehicles make it a promising alternative to traditional engines, offering a more efficient, more cost-effective, a cleaner solution

for the transportation sector. (Wallington, Henshaw and Ting, 204). Regardless, of the advantages of using hydrogen as fuel in internal combustion engines, some crucial challenges and disadvantages need to be addressed. Mainly of the major challenges, of them is the production and infrastructure of hydrogen. Especially, the production of green hydrogen is expensive and energy-intensive. The infrastructure of hydrogen refuelling is under development. Whereas, gasoline and electric stations are fully developed. Due to the low density of hydrogen in gaseous form, storage and transportation are highly challenging and need high-pressure tanks, which can lead to energy losses and increased costs.

Another challenge associated with hydrogen is safety concerns. In Hydrogen internal combustion engines, due to high combustion temperatures, the combusted hydrogen can lead to the formation of nitrogen oxides(NOx). (Koten, 2018)

Moreover, hydrogen is highly flammable, and handling requires tough safety measures. However, the advancements in hydrogen tank design and safety protocols have significantly reduced these risks, making hydrogen as safe as conventional fuels when properly managed.

Ricardo, a distinguished multinational corporation, has pioneered the development of WAVE, a state-of-the-art engine simulation package designed to elucidate the complex interactions between pressure waves, mass flow, and energy losses in ducts, plenums, and manifolds of different systems and machines. This sophisticated program integrates time- dependent fluid dynamics and thermodynamical calculations. Leveraging a one-dimensional formulation to provide a comprehensive simulation environment. A notable feature of WAVE is its versatility in accommodating an enormous range of working fluids, including air- hydrocarbon mixtures, air, liquid fuels, and combustion products. Thereby, enabling the automotive industry to simulate and optimize complex systems with precision and accuracy. (Ricardo, 2004)

Particularly, the compression ratio and Lambda have a significant influence on enhancing thermal efficiency and power output by facilitating spare complete combustion. Additionally, hydrogen's distinctive properties, such as its high flame speed and difficulty, affect combustion dynamics, making it indispensable to carefully adjust engine speed and load to optimize performance.

However, Lambda is particularly vital in hydrogen engines due to hydrogen's unique property of having a wide flammability range. Operating at lean conditions can significantly reduce NOx emissions. Nevertheless, this comes at the cost of reduced engine power and efficiency. With a combination of simulations and experiments, this study aims to optimize the balance between maximizing efficiency and NOx emissions. The expected outcome of this research will provide valuable insights into the design and operation of hydrogen engines.

This research delves into the effects of four critical engine parameters — compression ratio, lambda(air-fuel ratio), engine load, and engine speed – on the efficiency and NOx emissions of hydrogen IC engines. Those parameters are crucial in determining the thermodynamic efficiency and environmental impact.

The primary objective of this research is to unwind the complex relationships between key engine parameters and their combined influence on the performance of hydrogen engines.

Hydrogen engines offer a promising solution to reduce greenhouse gas emissions. These engines produce zero harmful emissions at some point of use, with the only byproduct being water vapour. This makes them an alternative option for reducing air pollution and addressing concerns about climate change. By leveraging hydrogen engines, the UK can take a significant step towards a cleaner and more sustainable energy future.

AIM AND OBJECTIVES :

Aim: To find out the best hydrogen engine design for the highest efficiency and lowest NOx emissions under lean burn conditions.

Objectives :

Simulating 3 3-cylinder gasoline engine to create a benchmark of outputs, to compare with hydrogen engine.

- Investigating the effect of engine speed, engine load, compression ratio, and Lambda on hydrogen-fuelled internal combustion engines.

- Finding appropriate compression ratio and air-fuel ratio to run the hydrogen engine under lean burn conditions under particular speed and load.
- Comparing the results of stoichiometric gasoline engines and lean burn hydrogen engines.

METHODOLOGY:

For the simulation in Ricardo WAVE, the parameters of the Ford Eco Boost 1.0L gasoline engine are created to establish a benchmark for power output, emissions, and brake thermal efficiency. This baseline serves as a foundation for evaluating the performance of the final hydrogen engine model, allowing for a comprehensive comparison of the two engines.

A hydrogen engine is simulated under different speeds and loads like 1000, 1250, 1380, 1500, 2000, 2500, 3000, 3500, 4000, 4500, 5000, 5500, 6000 RPM's, with different engine loads of 13%, 22%, 25%, 28%, 38%, 47%, 55%, 66%, 76%, 83%, 76%, 83%, 91%, and 100% respectively.

Lambda of the engine is associated with Air-fuel ratio, different air-fuel ratios of 34(stoichiometric), 42, 48, 55, 65, 75, 84, and 94 are evaluated under lean burn conditions with respect to different compression ratios of 10, 11, 12.5, 13.5, 14.1, and 16.1. The lambda values corresponding to these air-fuel ratios are 0.99(stoichiometric), 1.23, 1.40, 1.67, 1.90, 2.20, 2.46, and 2.75 respectively.

Ricardo wave 1-D simulation software is a powerful tool used to enhance engine online performance and analyse each parameter of the engine in one-dimensional space which is based on digital twin technology. By simulating engine performance using Ricardo WAVE, researchers can reduce the need for expensive and time- consuming experimental testing.

WAVE uses the conservation of mass, momentum, and energy to calculate airflow with the help of a Quasi-one dimensional compressible model. (Ricardo, 2004)

The equations are:

Mass $$\frac{dm}{dt} = \sum \dot{m}$$

Energy $$\frac{dme}{dt} = \sum \dot{m}h + sources$$

Momentum $$\frac{dmu}{dt} = -A\frac{dp}{dx}dx + \sum \dot{m}u - losses$$

Combustion model(Ricardo, 2004)

Ricardo WAVE uses the Wiebe Wiebe-based combustion model to solve the given inputs.

The formula used by WAVE is:

$$W = 1 - \exp\left(-AWI\left(\frac{\Delta\theta}{BDUR}\right)^{(WEXP+1)}\right)$$

Where W = cumulative mass fraction burned Δθ = crank degree past start of combustion BDUR = user-entered 10-90% burn duration in crank degrees

WEXP = used-entered Wiebe exponent

AWI = internally calculated parameter to allow BDUR to cover the range of 10-90%

The combustion model necessitates four primary inputs: duration, Wiebe exponent, fuel burn fraction, and combustion timing. The duration parameter, specified in crankshaft degrees, captured the time required for 80% of the combustion process to occur, omitting the initial and final 10% of combustion. In contrast, the timing input, also expressed in degrees, corresponds to the point at which half of the combustion and heat release have taken place, denoted as the 50% burn point. (Vorst, Finegold, 1975)

The software provides valuable insights into the complex dynamics of internal combustion engines, helping researchers to better understand the relationship between the engine parameters and their impact on performance and emissions. (Ricardo, 2004)

A 3-cylinder gasoline engine needs to be built. Setting up a hydrogen internal combustion engine in Ricardo WAVE mainly involves two steps:

1. Creating a one-dimensional gasoline engine.
   Model build -1 (creating a cylinder gasoline engine)
   Model build -2(creating three-cylinder gasoline engine)
   Model build -3(integrating the turbocharger)
   Model build -4(building a 3-cylinder gasoline engine for the required parameters to compare with a hydrogen engine)
2. Converting the gasoline engine into a hydrogen engine.
   Model build -5 (creating hydrogen engine)

Creating a one-dimensional gasoline engine in Ricardo WAVE involves several steps:

Model build-1 :
(creating one cylinder gasoline engine)

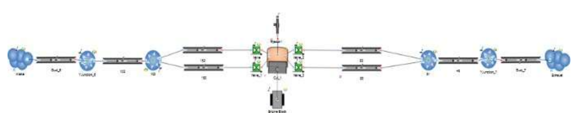

Figure 1: Single Cylinder Gasoline Engine

Getting familiarized with the WAVE interface: the model library has many engine components which can used and require modifications like bore, stroke and other major inputs.

Adding engine components to canvas :
Drag and drop each element such as cylinder, ducts, injector, and engine block from the wave library.

Defining components properties:
Defining component properties like bore, stroke, duct lengths, duct diameters, ambient air temperatures, valve diameters, and engine block parameters and selecting the appropriate air-fuel ratio for the SI engine.

Setting up combustion block mode:
Choosing the appropriate combustion model for the gasoline typically SI Wiebe combustion.

Running the simulation :
Simulating with the basic input that is required to simulate.

results analysis:
With the help of WAVE solver understand the workings of the engine and optimise the parameters such as air-fuel ratio, compression ratio, and speed for a better understanding of the engine.

Model build-2
(creating three-cylinder gasoline engine)

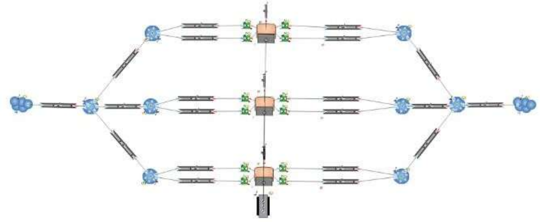

Figure 2: 3-cylinder Gasoline Engine

Adding up the cylinders:

Adding two more cylinders to the build model 1.

Defining the inputs :

Defining the same inputs like bore, stroke, duct diameter, duct lengths and compression ratio to the other two cylinders.

Engine block changes:

In build model 1 the default number of cylinders was set as one. However, this building model is setting up 3 3-cylinder engines, so making the required changes to the engine block is necessary according to the number of cylinders that are supposed to be evaluated.

Adding excess components:

Adding up the excess components such as Y junctions and connecting ports to simulate the engine.

Running the simulation and analysing the results :

By running the 3-cylinder engine the results will be evaluated by the WAVE solver and optimising the engine parameters for further requirements.

Model build-3 :

(integrating the turbocharger)

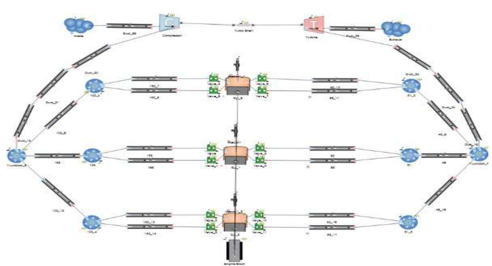

Figure 3 3-cylinder Gasoline Engine with Turbocharger

Adding turbocharger components :

From the same components library dragging down the components such as the compressor, turbine, and connecting shaft to set up the turbocharger to 3 cylinder model(build 2).

Configuring the turbocharger:

Specifying the turbocharger components' properties in the properties panel such as shaft inertia, mechanical efficiency, speed of turbocharger, and turbine maps.

Adjusting the intake and exhaust systems

Modifying the intake and exhaust sizes according to the requirement to accommodate the turbocharger and intercooler.

Updating the engine parameters

Adjusting the compression ratio, air-fuel ratio, and injection settings upon the requirement.

Running the simulation and analysing the results

After a successful simulation of the 3-cylinder turbocharger engine, further adjustments and modifications can be made for the optimization of the engine.

Model build-4

(building a 3-cylinder engine for the required parameters)

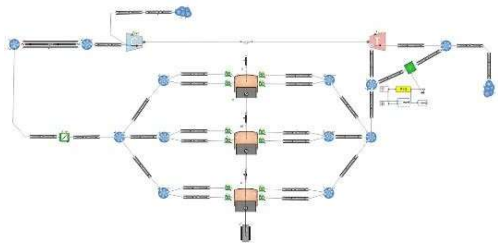

Figure 4 3-cylinder Turbocharger Gasoline Engine with Waste Gate

GETTING ENGINE SPECIFICATIONS :

Collect detailed specifications of the 3-cylinder engine, which includes a bore, stroke, connecting rod length, compression ratio, valve timing, duct lengths, duct diameters, and any other required parameters to simulate a gasoline internal combustion engine.

Initial model setup

Creating a new project in Ricardo WAVE. Initially project contains all the components, drag and drop every individual component which is required to set up the simulation.

Defining the engine parameters

Fuel type	Gasoline
Fuel system	Direct fuel injection
Number of cylinders	3
Valves per cylinder	4
Bore	71.9 mm
Stroke	82.0 mm
Connecting rod length	137 mm
Compression ratio	10.0:1
Firing order	1-2-3
Turbocharger compressor type	Variable geometry
Speed(rpm)	0-6000

Table 1 3 Cylinder gasoline engine specifications

COMPONENTS CONFIGURATION :

Intake and exhaust systems: - create the exhaust and intake model which includes a turbocharger. Adjust the geometries to match the engine specifications.

Combustion chamber

Configure the combustion chamber setting for gasoline combustion chamber characteristics. This includes setting up the appropriate air-fuel ratio, and ignition timing.

Fuel injection system

Set up the fuel injection system. As per the data the required fuel injection type is direct fuel injection.

Define operating conditions

Set the engine load and engine speed conditions for the simulation as mentioned in Table (1). Use an appropriate combustion model, such as Wiebe combustion.

ANALYSIS :

Performance and emissions analysis: - the WAVE solver solves the engine model and proves the outputs of all the parameters which include brake power, brake torque, NOx, CO, HC, and volumetric efficiency.

Document findings: - preparing a detailed report of the setup and simulation reports for the further optimization process.

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Model build-5 :
(converting the gasoline engine into to hydrogen engine)

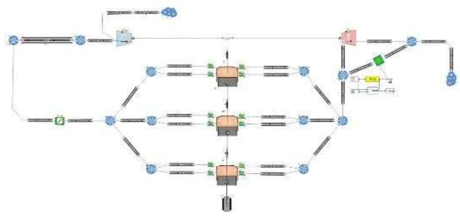

Figure 5 3- Cylinder Turbocharger Hydrogen Engine With Waste Gate

Converting the gasoline engine into a hydrogen engine consists of several steps:

SPECIFYING FUEL:
Ricardo WAVE has a default hydrogen fuel file, the same fuel file is used as the intake to modify the gasoline engine to a hydrogen fuel engine.

Defining the engine parameters :
Choosing the air-fuel ratio of hydrogen internal combustion engine:
A gasoline engine requires 14.7 parts of air concerning one part of fuel mass to burn under stoichiometry conditions, which comes with a composite of both carbon and hydrogen atoms. The gasoline has a complex hydrocarbon structure, which needs to react with oxygen. However, gasoline requires less air by mass for complete combustion.
Whereas, hydrogen is a much lighter fuel with a simple combustion process and produces only water as a byproduct. Hydrogen requires more air for complete combustion which requires around 34 parts of air for one part of hydrogen mass for better combustion without losing any fuel.

Selecting the appropriate injection system :
To reduce the risk of pre-injection, direct fuel injection is used. Many hydrogen engines use a direct fuel inject system for better performance.

Combustion model :
For the engine friction, the friction effective pressure of the gasoline engines typically falls under the 0.7 to 2.5 bar range based on the engine size. Whereas, hydrogen engines run at high speeds and require higher FMEP compared to gasoline engines around a scale of 2.8 to 4 bar compared to engine size and RPM range. (Knauder, 2019)
The present gasoline engines have an FMEP of 1.8 bar and to convert the engine from gasoline to hydrogen an FMEP of 3.8 is used for the precautionary safe conditions.
For the spark ignition hydrogen combustion engine, a mixture type of homogeneous is used by maintaining the same speed as 6000 RPM at a reference pressure of 1 bar.

Choosing a Better Compression Ratio
Hydrogen has an octane number of 130 or higher on the research octane number scale(RON). Whereas, normal gasoline has an octane number of around 87 and premium gasoline has an octane number of around 91 to 98 RON. Due to the higher octane number, the compression ratio of the hydrogen engine can be higher compared to the gasoline engine. The existing engine runs under a compression ratio of 10.0:1, by changing the fuel input of the same engine from gasoline to hydrogen a compression ratio from 10.0 to 16.1.0 can be used for the analysis and optimization process. (Sage et al., 2023) (Dincer Akal et al., 2020)

Injection timing
The injection timing in a 3-cylinder gasoline engine is direct fuel is used and it varies from 50^{0} to 300^{0} before dead centre (BTDC), depending on engine load, and speed. In a hydrogen fuel internal combustion engine same kind of fuel injection system is used, generally 40^{0} to 120^{0} BTDC or even closer to BTDC is used for the hydrogen engine. In some cases to avoid premature injection the

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injection timing could be delayed. (Knauder, 2019)

Emission control

Modifying the model to mainly focus on NOx emissions, as the hydrogen combustion process produces mainly water and NOx.

Turbocharger modification

Optimising the speed, boost, and wastegate of the turbocharger for the hydrogen combustion process. Using variable geometry can help stabilize the engine intake and exhaust gasses according to load and speed variations.

Simulation Analysis

Documenting the changes at each phase and optimising the engine parameters.

To simulate the hydrogen under lean burn conditions, an air-fuel ratio range from 34 to 94 was evaluated. The compression ratio ranges from 10.0 to 16.1 is used to evaluate the characteristics of each possible simulation to reduce the NOx and stabilise the efficiency.

Based on findings from the simulation outputs, potential improvements are made for the hydrogen internal combustion model.

RESULTS AND DISCUSSION:

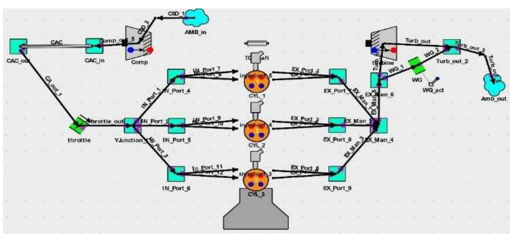


Figure 6 Ricardo WAVE simulation

The results in this section show the compression ratio, engine speed, engine load, and air-fuel ratio all have a significant impact on the efficiency and NOx emissions of the hydrogen- fuelled internal combustion engine.

Initially, a 3-cylinder engine fuelled by gasoline is simulated for the reference to compare the results of 3-cylinder hydrogen-fuelled engines under different compression ratios and different air-fuel ratios about optimal Brake thermal efficiency.

Version 0 :

3-cylinder turbocharged gasoline engine. Initially, a cylinder engine with a turbocharger was simulated and results were analysed with a stoichiometric compression ratio of 10.0:1 and a stoichiometric air-fuel ratio of 14.7.

Brake thermal efficiency with speed and brake torque

The plot(figure 7) illustrates the relationship between speed, torque and brake thermal efficiency. The x-axis and y-axis represent speed and brake torque power respectively. The speed of the engine is measured in RPM and torque is measured in N*m. The colour contours on the plot indicate the brake thermal efficiency of the gasoline engine, which goes with the colour bar providing a visual representation of brake thermal efficiency. The colour bar from blue to red corresponds with lower to higher efficiency respectively.

A closer examination of the plot reveals the brake thermal efficiency peaks at moderate engine speeds ranging from 2000 to 3500 RPM, and higher brake torque values, where the contour changes to warm colours, indicating an efficiency of 32 to 33%. Contrary, efficiency decreases at both extremely low and high speeds, which can be absorbed from the plot.

From a practical perspective, the engine operates most efficiently within the mid-range speed and torque zones, which provides optimal brake thermal efficiency. However, at the lower and higher speeds, lower efficiency can be absorbed from the plot.

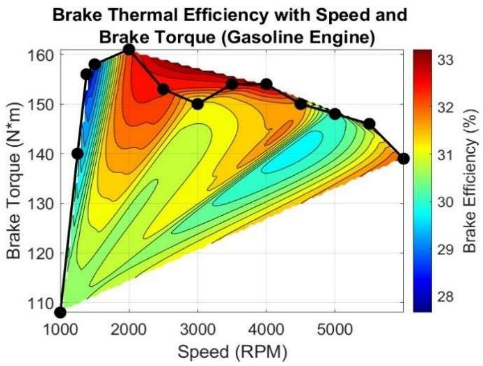


Figure 7 Effect of Speed on brake thermal efficiency and Brake Torque of Gasoline engine

Brake thermal efficiency with compression ratio and NOx.

The contour plot(figure 8) represents the correlation between NOx, speed, and brake thermal efficiency. The x and y-axis represent the speed and NOx of the gasoline engine respectively. The colour bar represents the brake thermal efficiency of the engine at each RPM. The colour range from blue-red represents lower to higher brake thermal efficiencies.

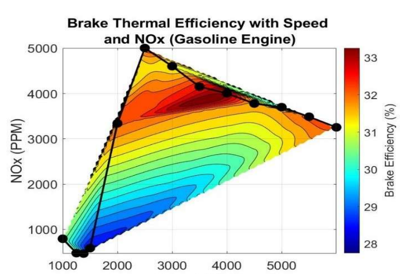
A detailed analysis of the plot shows a positive relationship between NOx emissions and engine speed, with higher NOx emissions related to higher engine speeds above 3000 RPM. The red region represents the higher efficiency of up to 33%, simultaneously, at lower speeds below 2000 RPM which is around 28-30 %. From the plot, it can be absorbed that the brake thermal efficiency with speed and NOx emissions exhibits an uncertain relationship.

From a practical perspective, it can be absorbed that the optimal brake thermal efficiency can be achieved at moderate to higher speeds, where NOx emissions are higher, but operating at immoderate high NOx levels may lead to diminishing returns in efficiency.

From the speed vs brake torque plot, the optimal brake thermal efficiency of 32-33% can occur around speed ranges of 2000 and 3500 RPM. In the same region, brake torque is also at peaks between 150-160 N*m. In the plot speed vs NOx emissions, the highest brake thermal efficiency of 32 to 33 % takes place at the 3000 to 4000 RPM speed range. Regardless, the brake thermal efficiency of the engine starts diminishing from 4000 RPM with respect to the increase in speed. At a speed range of 2000 to 3500 RPM the engine produces moderate NOx emissions.

Based on the analysis, it can be absorbed that, the optimal speed range to achieve a balance between NOx emissions, brake thermal efficiency, and brake torque lies between 2500 and 3500 RPM. At those speed ranges a higher brake efficiency of 32 to 33 % can be absorbed and, moderate NOx emissions, can be absorbed with strong brake torque ranging from 150 to 160 N*m.

Figure 8 Effect of speed on brake thermal efficiency and NOx emissions of Gasoline engine



Version 1

The hydrogen engine is simulated with a compression ratio of 10.0:1 and an air-fuel ratio of 34 which are stoichiometric conditions.

Brake thermal efficiency with speed and brake torque(Hydrogen engine)

The graph(figure 9) represents the relationship between brake thermal efficiency, torque, and speed for a hydrogen engine. In the colour spectrum range blue-red zone, the highest efficiency of the hydrogen engine is achieved in at red zone, where the engine operates at high torque and low-to-moderate RPMs, which results in a higher brake thermal efficiency of 34%. It can be absorbed from the graph, the hydrogen engine produces high torques at low speeds. In contradiction, the blue zone, marked at higher RPM and low torque indicates lower efficiency, with a brake thermal efficiency of 24%.

At low-to-moderate speeds with higher torque, the engine can convert a large portion of fuel energy into useful power which results in higher efficiency. Simultaneously, at high speeds and low torque, the engine experiences an increase in friction and heat loss which leads to a decrease in efficiency. At an RPM range of 1400-3000 RPM, the engine operates at higher efficiency and produces the highest torque of 170-180 N*m.

Prolonged operations in the low-efficiency zone, marked by low torque and higher RPMs, should be avoided to reduce energy losses and improve overall brake thermal efficiency.

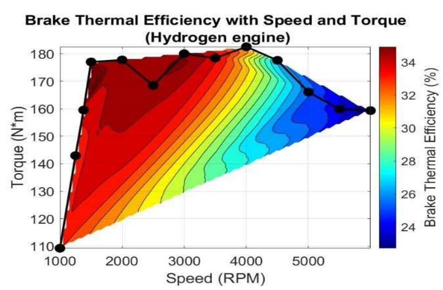


Figure 9 Effect of speed on brake thermal efficiency and brake torque of Hydrogen engine

Brake thermal efficiency with speed and NOx

The graph(figure 10) represents the significant relationship between NOx emissions, speed, and brake thermal efficiency. The x-axis and y- axis represent speed and Torque respectively. The spectrum range from blue-red represents the brake thermal efficiency from lower(~24%) to higher (~34%).

After a detailed examination of the plot reveals, the low engine speeds(1000-2000 RPM), the brake thermal efficiency, ranging from 32% to 34%, and NOx emissions are relatively low, around 500 to 1500 RPM. By absorbing the graph it can be suggested that the hydrogen engine Can be operated more efficiently at lower speed while producing fewer emissions. However, as the speed increases to 2000-3500 RPM, the brake thermal efficiency remains higher, but the NOx emissions exhibit a sharp increase, much higher at 4000 RPM. This indicates that the engine performance is optimised at the expense of increased NOx emissions.

At higher speeds of 4000-6000 RPM, the brake thermal efficiency diminished by around 28- 30%, simultaneously, NOx emissions decreased. It indicates that, at higher speeds, the engine becomes less efficient, but the NOx emissions are reduced.

By comparing both plots, the optimal RPM for obtaining high torque with low NOx emissions with respect to brake thermal efficiency occurs at a RPM range around 1000 to 2000 RPM with a brake thermal efficiency of 34%.

The NOx emissions are lower at the RPM range of 1500-2500 RPM, where brake thermal efficiency is still relatively high, as the speed increases above 3000 RPM the efficiency tends to decrease. The optimal RPM range considering high brake thermal efficiency, low NOx emissions and high brake torque would be around 1500-3500 RPM. This specific range of RPM provides a balance with a responsible high thermal efficiency of 32-34%, with high torque and manageable NOx emissions.

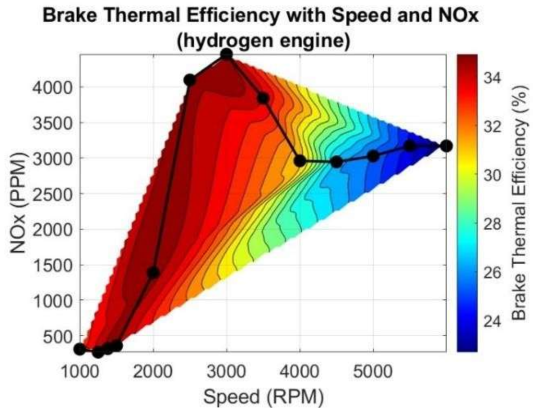


Figure 10 Effect of speed on brake thermal efficiency and NOx emissions of Hydrogen engine

Version 2

An RPM of 3500 and engine load of 66% are used to test different air-fuel ratios by stabilizing compression ratio 10. To find out the effect of different air fuel ratios under lean burn conditions.

Brake thermal efficiency with AFR and NOx

The plot(figure 11) illustrates the relationship between NOx emissions and Air-fuel ratio and brake thermal efficiency. The colour spectrum range is blue-red representing the efficiency of the hydrogen under different Air-fuel ratios and their NOx emissions under a speed range of 3500 RPM. The plot demonstrated that the NOx emissions are higher at lower Air-fuel ratio values of 40-55 and diminished significantly as the air-fuel ratio increases, reaching lower levels below 1000 PPM at higher air-fuel ratios(leaner mixture 80+).

However, the brake thermal efficiency reaches its peak at around 34% in the lower air-fuel ratios ranging from 40-55 AFR. Where NOx emissions are also highest. As the air-fuel ratio increases, engaging more leaner mixtures, the brake thermal efficiency drops and reaches the lowest efficiencies of around 22-44%, which takes place close to 90.

The optimal AFR range to balance both NOx emissions and high brake thermal efficiency is identified as around 50-60 AFRs. In these regions, the NOx emissions are moderate and the brake thermal efficiency remains relatively high(30-32%), offering a better settlement between emissions and engine performance.

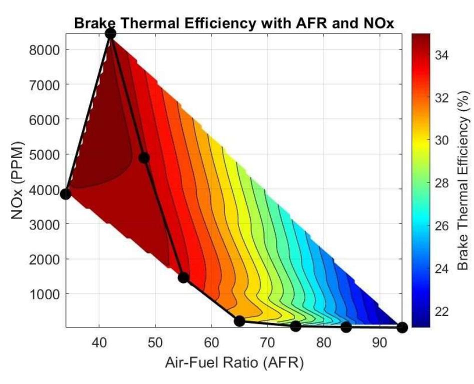


Figure 11 Effect of air-fuel ratio on brake thermal efficiency and NOx emissions in hydrogen engine

Brake thermal efficiency with AFR and Torque:

The contour(figure 12) plot represents the relationship between brake torque and air-fuel ratio for a

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hydrogen engine, by considering brake thermal efficiency of different air-fuel ratios by considering compression ratio 10. The engine produces higher torques around 160 N*m at lower air-fuel ratios of around 30-40. As the air-fuel ratio increases the torques start to depress with respect to a decrease in brake thermal efficiency.

A closer examination of the plot reveals that the brake thermal efficiency of the engine is maximum at a lower AFR range of around 40- 55, where both torque and efficiency are optimised. As the air-fuel ratio moves towards a leaner mixture, both torque and efficiency decline substantially, with the blue region indicating a low efficiency of around 22% which corresponds to the lower torque output of the engine. However, the red area in the plot donating higher efficiency, and high torque.

The optimal efficiency between the torque and the different ranges of air-fuel ratios is around 40-55, beyond this point the performance metrics deteriorate. By operating the hydrogen engine at these AFR conditions the performance of the engine can be optimised under lean burn conditions while minimizing energy losses.

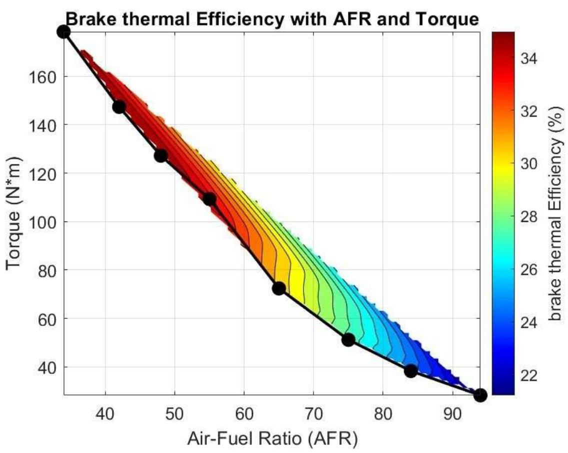


Figure 12 Effect of air-fuel ratio on brake thermal efficiency and brake torque in hydrogen engine

Version 3

An RPM range of 3500 RPM and an Air-fuel ratio of 55(lambda 1.67) is used to evaluate the effect of compression ratios of a hydrogen internal combustion under lean-burn conditions.

Brake thermal efficiency with compression ratio and NOx.

The graph(figure 13) represents the relationship between compression ratios and their NOx emissions under a stable speed range of 3500 RPM, with respect to the brake thermal efficiency of each compression ratio. The colour gradient blue region represents lower brake thermal efficiency(~34%), and the red region represents higher brake thermal efficiency(~35.5%).

As the compression ratio increases from 10 to 16.1, the NOx emissions exhibit a significant rise from 1600 PPM to 2800 PPM respectively. From the plot, it can be absorbed that, the NOx emissions are higher at the compression ratios of 15-16.1. moderate compression ratios around 13-15, the was able to produce optimal brake thermal efficiency, extremely at 14.1 compression ratio around 35.5 % efficiency. Optimizing the compression ratio is crucial for achieving high brake thermal efficiency, which plays a vital role in evaluating engine performance.

The plot highlights the trade-off between brake thermal efficiency and NOx emissions, increasing the compression ratio improves the engine efficiency, but it also leads to an incredible rise in NOx emissions. To strike a balance between high efficiency and moderate NOx emissions, a compression ratio of 14.1 offers an optimal compromise, by achieving a brake thermal efficiency of around 35.5% by limiting the NOx emission compared to higher compression ratios.

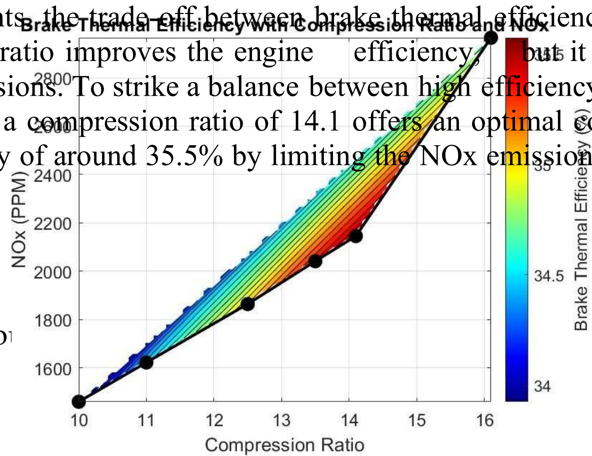


Figure 13 Effect of compression ratio on brake thermal efficiency and NOx emissions in hydrogen engine

Brake thermal efficiency with compression ratio and torque

The plot(figure 14) illustrates the relationship between the brake torques of different compression ratios and their brake thermal efficiencies, represented by a colour gradient. The blue region represents the lower efficiency(~34%). Simultaneously, the red region represents the higher brake thermal efficiency(~35.5%). Notably, as the compression ratio increases from 10 to 16.1, the torque exhibits a gradual decline, decreasing from approximately 108 N*m at a compression ratio of 10 to 90 N*m at a compression ratio of 16.1. this trend suggests that the torque output is inversely related to the compression ratio, with significant implications for engine performance.

A closer examination of the plot reveals that the brake thermal efficiency improves as the compression ratio increases. At a compression ratio of 10, the efficiency is lower around 34% as indicated by blue regions. Conversely, the higher efficiency, reaching up to 35% occurs at compression ratios around 14-16.1 as denoted by red areas. The plot highlights that compression ratio optimisation plays a critical role in achieving high brake thermal efficiency, a key parameter is evaluating the engine performance under lean burn conditions. However, the plot under-scores the trade-off between brake thermal efficiency and torque output. By increasing the compression ratio the efficiency is enhanced, and it comes with the cost of reduced torque output. A balance between these parameters, a compression ratio of 14.1 appears to offer a reliable compromise, where efficiency improves significantly without a drastic drop in torque.

A compression ratio of 14.1 and an air-fuel ratio of 55 would be suitable for hydrogen internal combustion to work under lean burn conditions without compromising both the performance and brake thermal efficiency.

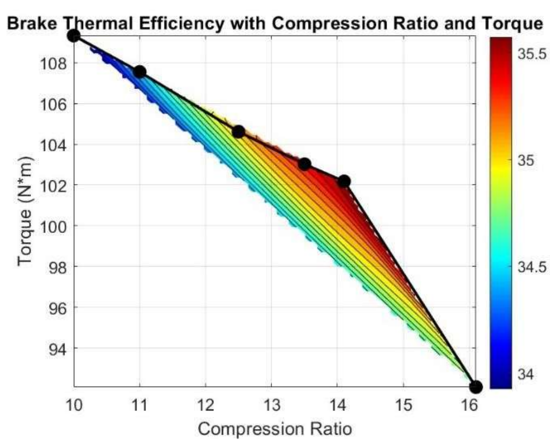


Figure 14 Effect of compression ratio on brake thermal efficiency and brake torque in hydrogen engine

DISCUSSION :

Version 0 is the existing 3-cylinder turbocharged gasoline engine with a compression ratio of 10.1:1 and air-fuel ratio of 14.7. the engine was simulated in Ricardo WAVE software to create a baseline to evaluate the results of a hydrogen internal combustion turbocharged engine, which is analysed under different combinations of air- fuel ratios and compression ratios to find the optimal performance concerning brake thermal efficiency. The engine was able to produce 32- 33% efficiency at a range of 2500-4000 RPM.

Version 1 is a hydrogen internal combustion engine. The same engine specifications as gasoline are used to simulate the engine with the help of Ricardo WAVE software. A compression ratio of 10 and air-fuel ratio of 34 is used, under stoichiometric conditions to understand the effect of hydrogen in internal combustion engines. The engine hydrogen engine was able to produce the highest efficiency of 34% at 2000-3500 RPM and the torque range was around 170-180 N*m.

The average speed range of 3500 RPM was used to simulate different compression ratios and air fuel ratios.

After running various simulations with different air fuel ratios and different compression ratios, version 2 and version 3 were simulated.

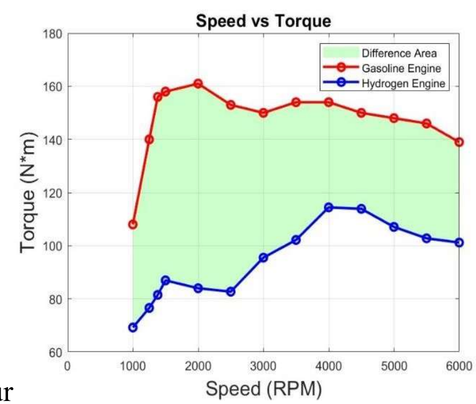
Version 2 is the hydrogen engine, by stabilizing the speed to 3500 RPM with a compression ratio of 10, air-fuel ratios of 34, 42, 48, 55, 65, 75, 84, and 94 were simulated, to understand the effect of efficiency at each air-fuel ratio. A better volumetric efficiency was obtained with a compression ratio of 10 and an air-fuel ratio of 55(lean)(Lambda 1.7).

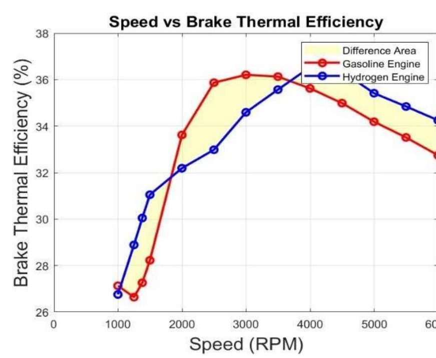
Version 3 is a hydrogen engine, by stabilizing the air-fuel ratio 55 different compression ratios 10, 11, 12.5, 13.5, 14.1 and 16.1 were evaluated to find the better compression ratio suitable for the hydrogen engine. Due to hydrogen's higher octane number of 130 RON, the hydrogen engines are capable of running under higher compression ratios.

The engine was able to produce a brake thermal efficiency of around 35-35% at a compression ratio of 14.1 under lean burn conditions with 2145 PPM of NOx emissions and a torque of 102 N*m, whereas, with the compression ratio of 14.1, the engine was able to produce 35- 35.5% and as the compression ratio increased the brake thermal efficiency of the engine started to reduce gradually.

Comparison between version 0 and version 3, The gasoline engine was producing 32-33% brake thermal efficiency under stoichiometric conditions, whereas the hydrogen was producing 34-35% brake thermal efficiency under lean burn conditions with an air-fuel ratio of 55 and compression ratio of 14.1 and lambda corresponding to these conditions is 1.6.

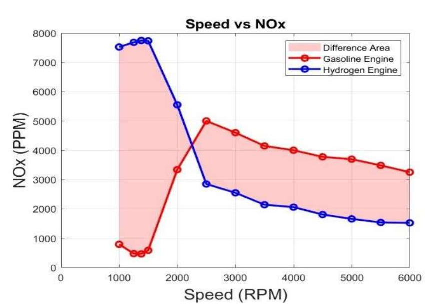
A graphical representation of both engines (Ford Eco Boost 1.0L gasoline and hydrogen engine) is





presented in Figur es 15, 16, 17 and 18, to compare the performan

Figure 15 Hydrogen and Gasoline engine torque vs speed



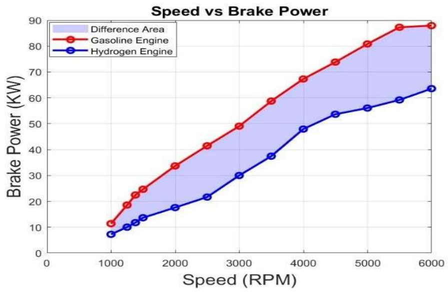


Figure 16 Hydrogen and Gasoline engine brake power vs speed

Figure 17 Hydrogen and Gasoline engine NOx vs speed

CONCLUSIONS:
A hydrogen engine with a compression ratio of 10 and air-fuel ratio of 34 can accomplish higher brake thermal efficiency at low-moderate speeds and loads under stoichiometric conditions with brake thermal efficiency of 34%.
Due to hydrogen's higher octane number(130 RON), hydrogen internal combustion engines can perform under higher compression ratios with an Air-fuel ratio of 55 under lean burn conditions with moderate NOx emissions and optimal performance with brake thermal efficiency of 35.5%.

FUTURE WORK :
Future work can focus on optimizing the volumetric performance across the wide range of RPMs, specifically, in the low and high regions of RPMs, where efficiency is diminished. This can be carried out by looking into various advanced intake and exhaust valve timings strategies, such as VVT to improve the air intake and combustion efficiency. By developing turbocharged techniques to optimize the air intake at higher speeds.
Techniques like the exhaust gas recirculation method can be used to reduce NOx emissions and another method like selective catalytic reduction can help to convert the harmful gases into harmless gases. Can investigate these methods, by maintaining efficiency to find a balance between performance and reduction of NOx emissions.
By pursuing these methods, significant advancements can be made to optimize engine performance.

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