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Conference paper

Towards a more powerful hydrogen engine

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ABSTRACT

This research examines the operational efficiency of a single-cylinder hydrogen engine through simulations conducted in OpenModelica. The research focuses on analyzing the combustion characteristics, heat release, temperature, and pressure at varying engine speeds of 1700, 2000, and 2500 rpm. The combustion process is modeled by applying the Wiebe function to represent the proportion of fuel mass that is burned, while the heat released by combustion is calculated using a formula incorporating the fuel mass, lower heating value, and combustion efficiency. The study presents detailed simulations of in-cylinder temperature, heat release rate, and pressure profiles, and examines how these parameters vary with engine speed. Results reveal that peak temperatures and heat release rates increase with engine speed, indicating more intensive combustion at higher speeds. The pressure curves and power output also show significant changes with speed, with higher engine speeds leading to increased power output and improved engine efficiency. This study provides insights into the hydrogen engine's behavior under different operating conditions, highlighting the impact of engine speed on performance metrics.

1. INTRODUCTION

High emissions from compression ignition (CI) engines, particularly diesel engines, pose a significant challenge due to the high temperatures within the combustion chamber. These elevated temperatures lead to the formation of harmful radicals and reactive species, which disrupt stable compounds and increase pollutant emissions. Researchers have proposed using hydrogen as an alternative fuel to enhance the efficiency and combustion of traditional diesel engines (Taghavifar et al. 2014). However, hydrogen use also increases in-cylinder temperatures, potentially exacerbating issues like combustion knock and high auto-ignition temperatures (Welch & Wallace, 1990; Gomes et al. 2009).

Research in this area primarily falls into two categories: burning pure hydrogen in CI engines and blending hydrogen with diesel in a combustible mixture (Ghazal, 2013; Zhou et al. 2014). Alrazen et al.

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(2016) conducted a numerical analysis of how blending hydrogen (H2), compressed natural gas (CNG), and diesel affects diesel engine combustion and emissions. The researchers adjusted the air/fuel ratio to compare the tri-fuel configuration of diesel, CNG, and hydrogen with the dual-fuel setups of diesel-CNG and diesel-hydrogen. Results indicated that incorporating gaseous fuels led to higher peak pressure and temperature, especially at lower and moderate excess air ratios. Another study employed computational fluid dynamics (CFD) simulations to investigate the effects of varying hydrogen, methane, and diesel blend ratios on combustion behavior and emissions in a diesel engine (Mansor et al. 2017). The results indicated that hydrogen extends the ignition delay, but increasing the diesel proportion might reduce peak pressure. However, a linear increase in peak pressure was also observed when hydrogen was present. Rocha et al. (2016) A study investigated the effects of hydrogen supplementation on compression ignition (CI) engine performance using biodiesel-blended fuel. The experimental results demonstrated that introducing hydrogen into the engine's intake air stream led to two significant improvements: a decrease in the specific fuel consumption rate and an enhancement in overall thermal efficiency. They also suggested that hydrogen would lower CO and HC emissions by accelerating combustion kinetics.

A recent numerical study used fuzzy logic to estimate total heat transfer from a hydrogen-powered diesel engine (Taghafivar et al. 2015). The model, which employed the Trimf membership algorithm, demonstrated a strong correlation with a coefficient of determination (R^2) of 0.999. The study found that adding hydrogen increased the mixture's diffusivity, which enhanced cumulative heat release. Experimental studies on hydrogen enrichment, where hydrogen and diesel are injected separately, are limited (Karagoz et al. 2016; Sandalci et Karagoz, 2014). The experimental investigation examined the impact of varying operational parameters - specifically engine load conditions and hydrogen concentration levels - on key performance indicators. The analysis encompassed both efficiency metrics (including indicated specific fuel consumption and brake thermal efficiency) and exhaust emissions characteristics, with particular attention to carbon monoxide, nitrogen oxides, and particulate matter concentrations.

Multiple research investigations into hydrogen dual-fuel systems for diesel engines have been synthesized in the literature. The collective findings indicate that the integration of hydrogen fuel with exhaust gas recirculation technology presents a promising approach for optimizing the trade-off between emissions and efficiency in diesel propulsion systems. Specifically, this combination shows potential for simultaneously managing particulate matter and NOx emissions while maintaining favorable brake-specific fuel consumption characteristics (Banerjee et al. 2015).

This study employs OpenModelica simulations to explore the performance of a single-cylinder hydrogen engine across speeds of 1700, 2000, and 2500 rpm. The research highlights how increasing engine speed impacts in-cylinder temperature, heat release rate, and pressure, with higher speeds leading to more intense combustion and improved power output. These findings offer insights into optimizing hydrogen engine performance and efficiency under varying operational conditions.

2. DESCRIPTION OF MODEL

2.1 Combustion model

The heat released by combustion is calculated by my following formula:

$$Q_{fuel} = m_{fuel} \frac{d(MFB)}{d\alpha} LHV \eta com \tag{1}$$

We assume that the combustion is complete and therefore we impose ηcom = 1.

To calculate the fuel weight:

$$m_{fuel} = \frac{m_{air}}{AF.\lambda} \tag{2}$$

AF Mass ratio air fuel and λ air factor

$$\lambda = \frac{AF_{actuelle}}{AF_{stocheometrique}} \tag{3}$$

The rate of fuel combustion progress, expressed as the mass fraction burned, can be mathematically modeled using the Wiebe combustion function (Zareei & Rohani, 2021):

$$MFB = 1 - \exp(-ay^{m+1}) \tag{4}$$

Or is determined by:

$$y = \frac{\alpha - \alpha_0}{\alpha_b} \tag{5}$$

The combustion duration represents a multifaceted phenomenon influenced by several thermodynamic and physicochemical variables, including thermal conditions, pressure dynamics, turbulent flow characteristics, mixture composition, and reaction kinetics. While empirical correlations linking engine rotational speed to combustion duration exist in the literature, this analysis employs predetermined combustion intervals. The shape parameters of the combustion profile are calibrated to align with experimental observations, following established values documented in fundamental internal combustion engine research (Heywood, 1988).

2.2 Case Study

This study investigates the performance of a single-cylinder hydrogen engine using computer simulations. We modeled the engine's combustion, heat release, temperature, and pressure characteristics at different speeds (1700, 2000, and 2500 rpm) using OpenModelica software. They analyzed how engine speed affects key performance metrics and presented the results through various graphs, providing insights into the engine's behavior under different operating conditions without extensive physical testing.

Table 1: Engine specifications

Parameters	Value
Bore	86 mm
Stroke	82 mm
displacement	448 cm^3 /cylinder
Compression ratio	11.5:1
Connecting rod length	107 mm

2.3 Numerical Methodologies

Define abbreviations and acronyms the first time they are the modeling in this study is carried out in the OpenModelica environment using the Modelica language. A high-level declarative language for describing mathematical behavior is called Modelica. It is frequently used in engineering systems and makes it simple to explain how various kinds of engineering components such as springs, resistors, clutches, etc. behave. Then, these parts can be joined to create systems, subsystems, or even entire architectures. The simulation work utilizes an open-source computational environment that provides comprehensive capabilities for system modeling, numerical simulation, and optimization analysis. This freely accessible platform enables the development and execution of complex mathematical models. It is built on the Modelica modeling language.

3. RESULTS AND DISCUSSION

The in-cylinder temperature (T) as a function of crank angle (°CA) for three distinct engine speeds—1700 rev/min, 2000 rev/min, and 2500 rev/min—is displayed in the graph Fig. 1.

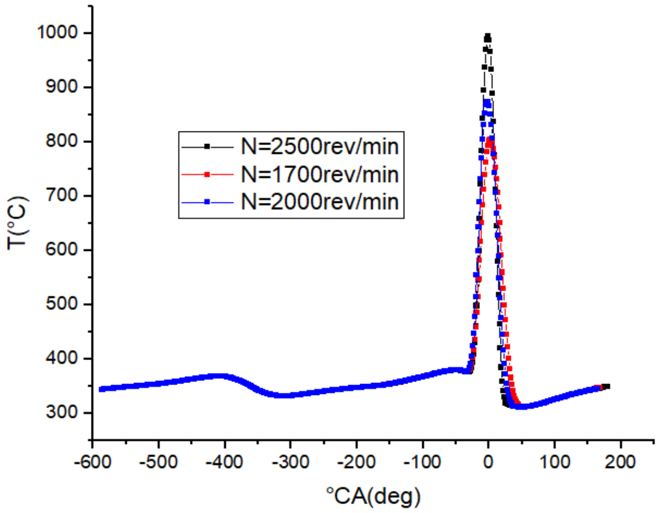

Fig 1. Variation of Temperature as a function of crankshaft rotation angle

The temperature remains relatively stable at around 300-400 °C during the compression and exhaust strokes, as indicated by the flat regions on the left and right ends of the curves. A sharp temperature increase is observed near the top dead center (TDC) (around 0° CA), corresponding to the combustion event. The peak temperature during combustion increases with engine speed, with the highest peak occurring at 2500 Rev/min, slightly higher than at 2000 Rev/min and 1700 Rev/min. Diese suggests that higher engine speeds result in mehr intensive combustion, likely due to higher air-fuel-mixture pressure and increased turbulence. Despite these differences, the peak temperatures are very close across the different speeds, indicating similar combustion efficiency. After the peak, the temperature rapidly declines, as the piston moves down during the power stroke, and the exhaust gases are expelled, consistent with the expected thermodynamic behavior after energy release in the combustion chamber.

Figure 2 illustrates the relationship between Heat Release Rate (HRR) and Crank Angle (CA) across three distinct engine operating speeds (1700, 2000, and 2500 rev/min).

The heat release rate (HRR) peaks sharply around 0 degrees CA for all three engine speeds, with maximum values ranging from approximately 30 to 50 J/deg. There is a slight shift in the peak position and shape as the engine speed changes, with the 2500 rev/min condition showing the highest peak HRR.

The heat release occurs over a relatively narrow crank angle range, spanning roughly from -20 to +20 degrees, while outside this range, the HRR is effectively zero for all speeds.

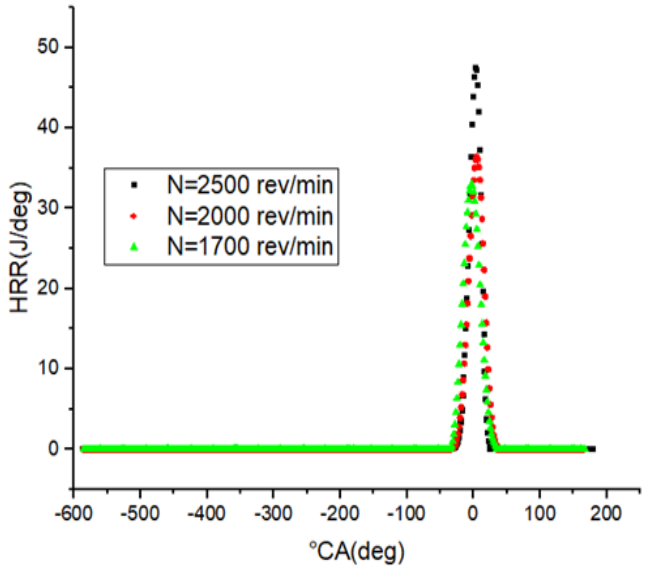

Fig 2. Variation of HRR as a function of crankshaft rotation angle

The cylinder pressure (P) for an internal combustion engine running at three distinct speeds—1700, 2000, and 2500 rev/min—is shown against the crank angle (CA) in this graph' Fig 3'.

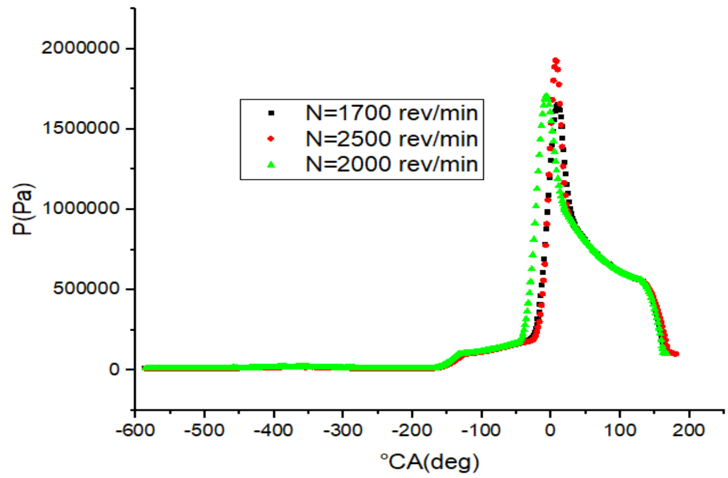

Fig 3. Variation of the pressure in the cylinder as a function of crankshaft rotation angle

The pressure curves follow a typical compression-combustion-expansion cycle, with peak pressures occurring slightly after 0° CA, reaching around 1.8-2.0 MPa. Higher engine speeds generally result in higher peak pressures. The compression phase begins around -180° CA, with pressure steadily rising until it reaches its peak. Afterward, a rapid expansion phase occurs, followed by a more gradual pressure decrease. The curves align closely during the compression and late expansion phases, diverging mainly near peak pressure. Slight variations in the timing and magnitude of peak pressure are visible between different engine speeds.

Figure 4 illustrates the relationship between engine speed (in rpm) and power output (in kW). The increase in power output from 9 kW to 17 kW as engine speed increases from 1700 to 2500 RPM is due to the interplay of increasing torque and angular velocity. The engine's efficiency improves, and it operates in a range where the combustion process and mechanical efficiency are optimized. This results in a significant increase in power output over this speed range.

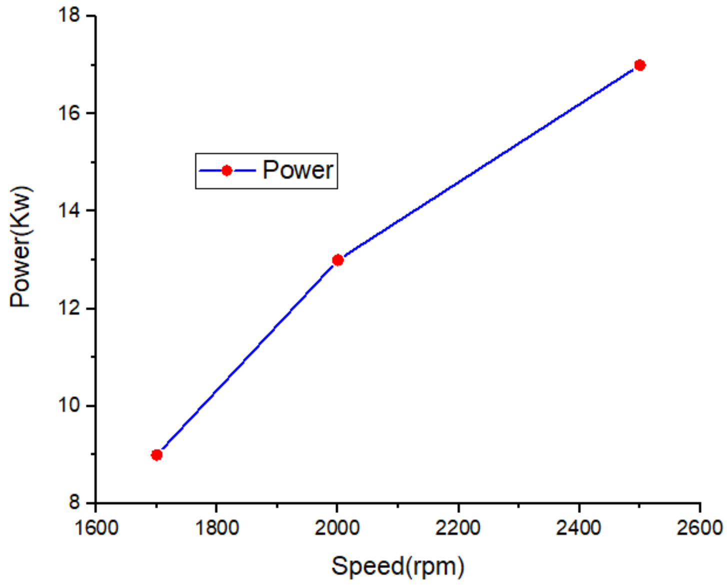

Fig 4: Variation of power as a function of Engine speed.

4. CONCLUSION

Analysis of the computational model reveals key performance characteristics of a hydrogen-fueled mono-cylinder engine operating at varying rotational speeds. The study demonstrates that engine speed significantly affects the in-cylinder temperature, heat release rate, and pressure, with higher speeds leading to more intense combustion and higher peak temperatures. The heat release rate peaks sharply near the top dead center and shifts slightly with varying speeds, with the highest values observed at 2500 rpm. Cylinder pressure increases with engine speed, reflecting higher combustion pressures and improved engine efficiency. The power output of the engine rises from 9 kW to 17 kW as engine speed increases from 1700 to 2500 rpm, indicating optimized combustion and mechanical efficiency at higher speeds. Overall, the findings underscore the importance of engine speed in influencing combustion dynamics and performance, providing a basis for further optimization and development of hydrogen internal combustion engines.

NOMENCLATURE

AF	Air-Fuel ratio	MFB	Mass fraction of burnt
P	Pressure [Pa]	LHV	Low heating value
T	Temperature [°C]	N	Engine speed
HRR	Heat release ratio [J/deg]	a, m	Wiebe parameters

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