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The influence of hydrogen addition on operational parameters values of ICE engine

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Abstract

Hydrogen, as a clean and renewable energy carrier, has attracted significant interest due to its potential to reduce greenhouse gas emissions when used in internal combustion engines and fuel cells. Research into dual-fuel systems, particularly in blends of conventional fuels with renewable alternatives, aims to address challenges related to pollutant emissions, and adaptability of existing engine technologies. This paper presents research on the Honda NHX 110 internal combustion engine (ICE), powered by dual fuels. The engine was fueled using the following mixtures of fuels: RON95 with methanol (M85), RON95 with ethanol (E85), M85 with hydrogen, and E85 with hydrogen. Experimental research was performed at different ignition advance angle (IAA) values. The effects of IAA changes on indicated work, mechanical power, torque, electrical power, and effective and mean effective loop pressure generated by the ICE engine are discussed. Finally, conclusions are drawn about the influence of IAA and hydrogen addition on nitrogen oxides and hydrocarbon emissions. These results highlight the potential of hydrogen as a transitional fuel while emphasizing the need for advanced strategies such as exhaust gas recirculation (EGR) and variable valve timing (VVT) to optimize dual-fuel ICE systems.

Keywords: Hydrogen addition; dual fuel; ICE engine, ignition advance angle; E85; M85

Introduction

The perspective of fossil fuel depletion offers a new view on the functioning of the European and worldwide energy markets [1] in the context of developing and accepting distributed energy generation sources [2].

A notable example of significant change is the energy and climate package adopted by European Union member states. This package sets targets for 2030- and 2050-time perspectives. The main goals in the 2030 horizon are to boost energy efficiency to 27%, the share of renewable energy sources in the energy market to 27%, and to achieve a 40% reduction in CO2 emission [3], relative to 1990 levels.

In Poland, the hydrogen economy could gain momentum, driven by the adoption of the national Hydrogen Strategy, which aims to integrate hydrogen into energy, industry, and transportation sectors by 2030 [4]. This aligns with global trends promoting hydrogen as a key component of decarbonization strategies and highlights the importance of research into dual-fuel systems as a transitional solution [5].

The climate package [3] is an impulse for new technology development, including the technologies of distributed energy generation [6], i.e., solid oxide fuel cells (SOFC) [7], molten carbonate fuel cell (MCFC) [8], proton-exchange membrane fuel cells (PEM) [9], Stirling engines [9], microturbines [6], organic Rankine cycles [1], and many others [10] in sustainable development. Among the mentioned distributed generation devices [1] ones that produce energy from alternative fuels [8,11] (i.e., methane [12], biogas [13], liquefied natural gas (LNG) [14], compressed natural gas (CNG) [15], methanol [16], dimethyl ether [17], ethanol [8], butanol [16] and other bio-derivative fuels [18], as well as capable of being fueled by solar fuels, such as hydrogen [19] and a mixture of hydrogen with other alternative fuels [20], i.e., hydrogen-enriched natural gas [21], hydrogen-enriched LPG [22], hydrogen-enriched WCO biodiesel [23]) can be distinguished, such as gas engines [24]. The meager power output of internal combustion engines (ICE) has become important [25]. Alternative fuels can fuel such engines [26] to generate electricity in distributed energy generation systems [27]. Much attention is given to hybrid prosumer micro-installations, which can cooperate with energy storage units and microgeneration systems [28]. Such micro-generation systems may include external combustion engines (ECE) [1], which can use multiple substances as fuel [29], including alternative fuels [30] and solar fuels such as hydrogen [31].

This study investigates the operation of a single-cylinder, 4-stroke ICE fueled by mixtures such as methanol and RON95 (15% methanol and 85% RON95 by volume, known as M85), RON95 with ethanol (15% of 99,99% pure ethanol and 85% RON95 by volume, known as E85), M85 with hydrogen (20% hydrogen and 80% M85 by volume), and E85 with hydrogen (20% hydrogen and 80% E85 by volume).

The research presented in this article is part of widespread research [9,11,15,16] conducted for various combustion engine rotational speeds and loads. Results for engine rotational speed n=4500rpm, λ=1, are measured at fully open throttle.

The primary objective was to evaluate the impact of a 20% volumetric hydrogen addition to M85 and E85 fuels on effective operating parameters, such as indicated work, mechanical power, torque, mean effective indicated pressure (MEIP) inside the cylinder, and electrical power of the HONDA NHX 110 engine. Additionally, the study aimed to assess the impact of hydrogen addition to M85 and E85 fuels on hydrocarbon and nitrogen oxide emissions.

The article is structured as follows: Section 2 describes the test stand, Section 3 presents the research results, and Section 4 summarizes the main conclusions.

Description of the ICE test stand

This section describes the test stand used to conduct a wide range of experimental research (a diagram and photograph of the test stand are shown in Figure 1). It consisted of the following elements:

- Honda NHX 110 four-stroke ICE (Figure 2),
- Electric machine - motor / generator,
- Programmable controller, i.e., Engine Management Unit (EMU) / Engine Control Management (ECM) (Figure 3),
- LabVIEW Software for measurement, diagnostics and control [9,11,15,16].

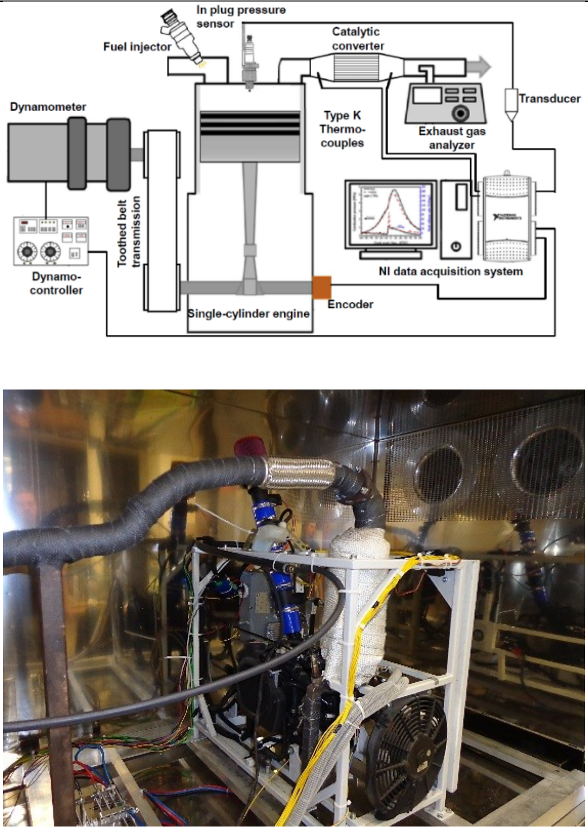


Figure 1: The scheme and the photograph of the test bench inside the Vötsch climatic chamber [16]

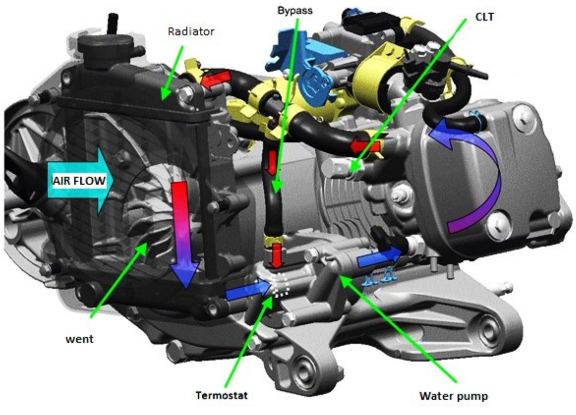


Figure 2: HONDA NHX 110 ICE

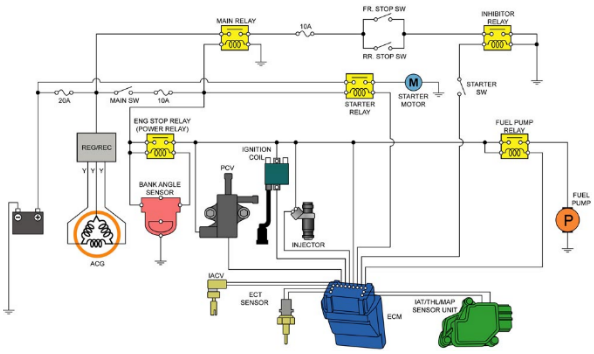


Figure 3: The scheme of the electronic control unit – ECM [16]

The main component of the test stand was a single-cylinder Honda NHX 4-stroke ICE with a displacement of 108 CCM power, rated by the manufacturer at 6.6 kW. The engine was water-cooled with a three-way catalyst (Figure 2). Three fuel injectors were used to provide fuel to the engine. The fiber optic pressure sensor and absolute rotary encoder acquired indicated pressure values.

The test stand was equipped with a dynamometer (Figure 4) [9,11,15,16,32]. Torque was transferred to the permanent magnet BLDC motor (which also functioned as a generator). Electrical power was supplied by means of the three-phase rectifier bridge, a transistor module (with microcontroller [9,11,15,16,32]), the resistor, the BLDC motor with permanent magnets, and supply voltage. The electric generator received the torque from the ICE shaft with synchronous belt drive. I=1.42 was the gear ratio between an electric motor and an ICE. A strain gauge beam measured the torque. A digital 14-bit absolute single-turn encoder that was linked to the measurement board in accordance with SSI standards was used to measure the crankshaft's rotation angle.

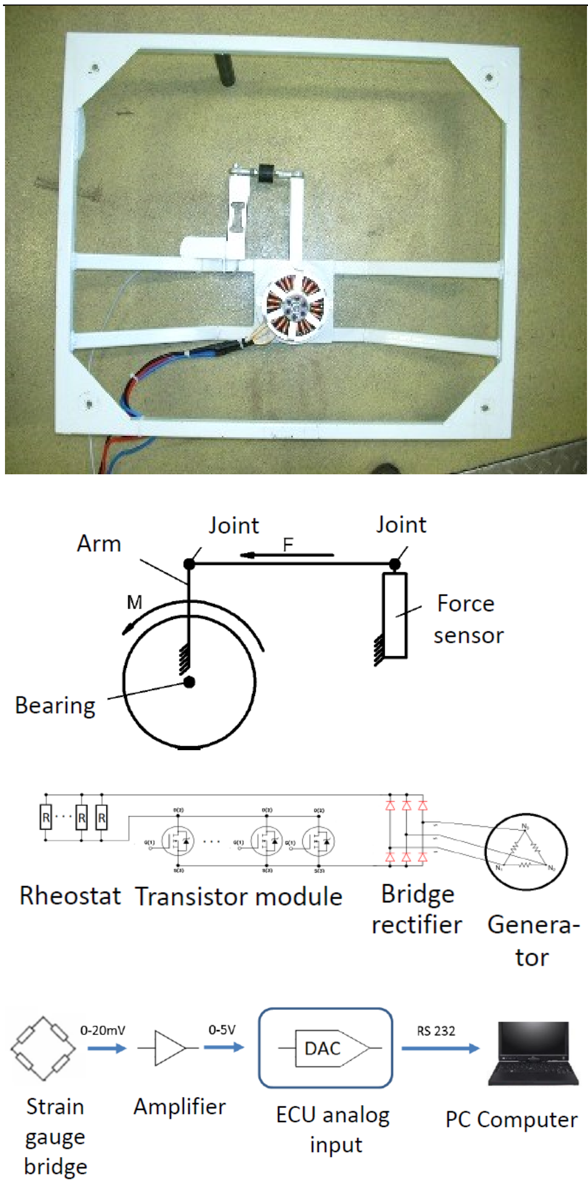


Figure 4: The scheme of the dynamometer system of HONDA NHX 110

The test stand featured a custom load generation system consisting of a permanent magnet BLDC motor (electric generator) coupled with the ICE by a toothed belt transmission and a load control unit for electric current control. A controllable resistor unit dissipated the generated electric energy. The detailed parameters of the test-stand equipment are in Table 1.

Table 1: Technical parameters of test-stand equipment

Parameter name	Unit	Value
Maximum voltage of three-phase bridge rectifier	V	400
Maximum current of three-phase bridge rectifier	A	300
Supply voltage	V	30 to 70
Speed constant	rpm/V	150
RPM limit	rpm	10 500
No load current and voltage	A, V	13, (at 20 V)
Measurement board: clock frequency	kHz	44.9
Measurement board: measurement precision	CA	0.5 (for 3800rpm)

The load system can control the electric current flow, thus controlling the generated load torque. During research, the system was set to automatically control the amount of current to ensure a set combustion engine rotational speed at open throttle.

The test stand allowed the generated load torque to be acquired using a load cell. This generated torque was proportional to the combustion engine torque. Before conducting the research, the system was calibrated. A programmable EMU was used to manage the engine [9,11,15,16,32]. The unit controls the parameters key to engine operation, such as fuel dosage and ignition advance angle (IAA). The primary technical data for the HONDA NHX 110 ICE engine are presented in Table 2.

Table 2: Technical data of HONDA NHX 110

Parameter name	Unit	Value
Maximum power	kW	6.6 (at 7500 rpm)
Torque	Nm	9.3 at 6250 rpm)
Swept volume	ccm	108
Compression ratio	-	11
The diameter of the throttle	mm	20
The stroke of the piston	mm	50
The diameter of the piston	mm	50
Demand for air	dm^3/min	405 (at 7500 rpm
Intake valve closing	deg	25˚ ABDC
Intake valve opening	deg	10˚ BTDC
Exhaust valve closing	deg	5˚ BTDC
Exhaust valve opening	deg	35˚ ABDC
Injector resistance	Ω	9-12 (at 20˚C)
Ignition advance	deg	14 deg BTDC (idle)

Experimental results

The ICE engine experimental research was performed in a climate chamber under steady operating conditions. The parameters are shown in Table 3.

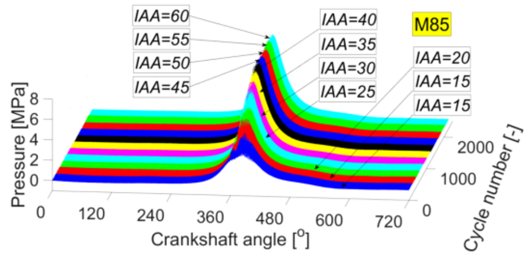
Table 3: Data of HONDA NHX 110 - tests in a Vötsch climatic chamber

Parameter name	Unit	Value
Temperature of intake air	K	298 ± 3
Atmospheric pressure	hPa	1009
Air-fuel equivalence ratio	-	$\lambda = 1$
Engine rotational speed	rpm	4500
Throttle position	-	fully open

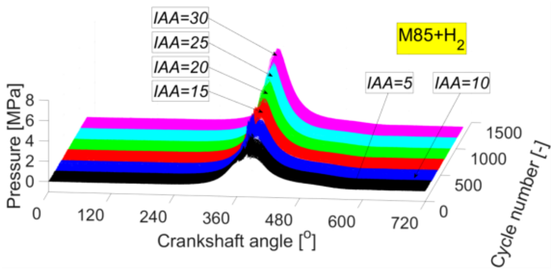
Figure 5 presents the effective indicated pressure (EIP) graphs achieved during several hundred work cycles for different fuel types: M85 (Figure 5a), M85+H2 (Figure 5b), E85 (Figure 5c), and E85+H2 (Figure 5d).

The measurements were carried out from IAA=15˚ to IAA=30˚ in the case of M85, from IAA=5o to IAA=30˚ in the case of M85+H2, and from IAA=5˚ to IAA=35 in the case of E85 and E85+H2. All measurements were performed with 5˚ increments.

The results presented in Figures 5 a-d) show that the pressure increases for all tested fuels with the increase of IAA.



(a)



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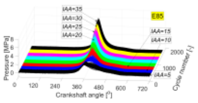

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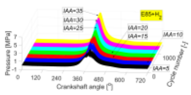
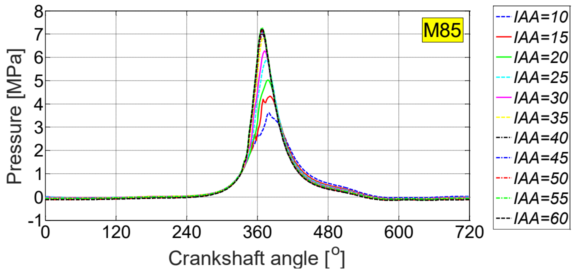


(d)

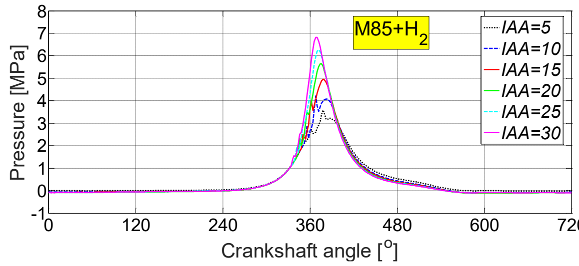
Figure 5: The graphs of indicated pressure for (a) M85, (b) M85+H2, (c) E85, and (d) E85+H2 for several hundred consecutive cycles, respectively

In Figure 6 a-d), the mean effective indicated pressure (MEIP) graphs are presented (averaged for a range between 5˚ CA to 720˚ CA) for various values of IAA for the tested fuels: M85 (Figure 6a), M85+H2 (Figure 6b), E85 (Figure 6c) and E85+H2 (Figure 6d).

The highest MEIP value of 7.29 MPa was achieved for M85 at IAA=55˚ (Figure 6a). The 20% volumetric addition of hydrogen for M85 and E85 negatively influences the maximum values of the MEIP.



(a)



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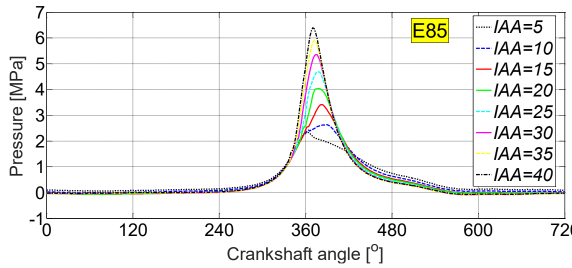

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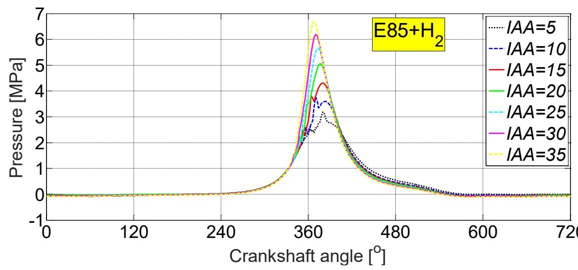

(d)

Figure 6: The influence of the IAA on MEIP values of pressure for tested fuels: (a) M85, (b) M85+H2, (c) E85, (d) E85+H2

Figure 7 illustrates the results for indicated work (Figure 7a), torque (Figure 7b), mechanical power (Figure 7c), and electrical power (Figure 7d) for ICE fueled by M85, M85+H2, E85, and E85+H2.

The highest value of the indicated work (211.4 J) (Figure 7a) was obtained for M85 at IAA = 50˚, while the lowest value (190.4 J) for E85+H2 at IAA = 35˚. The maximum value of electric power (Figure 7d) was obtained at IAA = 20˚ for E85+H2 – in this case, the electric power value was 3.59 kW, corresponding to a torque value of 11.3Nm. The lowest value of electric power was obtained for E85+H2 at IAA = 35˚.

The highest torque value was achieved when the engine was powered with M85 fuel (Figure 7b); at IAA = 25˚, the torque value was equal to 12.08 Nm, while the mechanical power was 5.98 kW

(Figure 7c). Based on the conducted tests, it was found that the best fuel for further usage is M85 without the addition of hydrogen. For the M85, the highest values of torque, mechanical power, electric power, indicated pressure and indicated work were obtained.

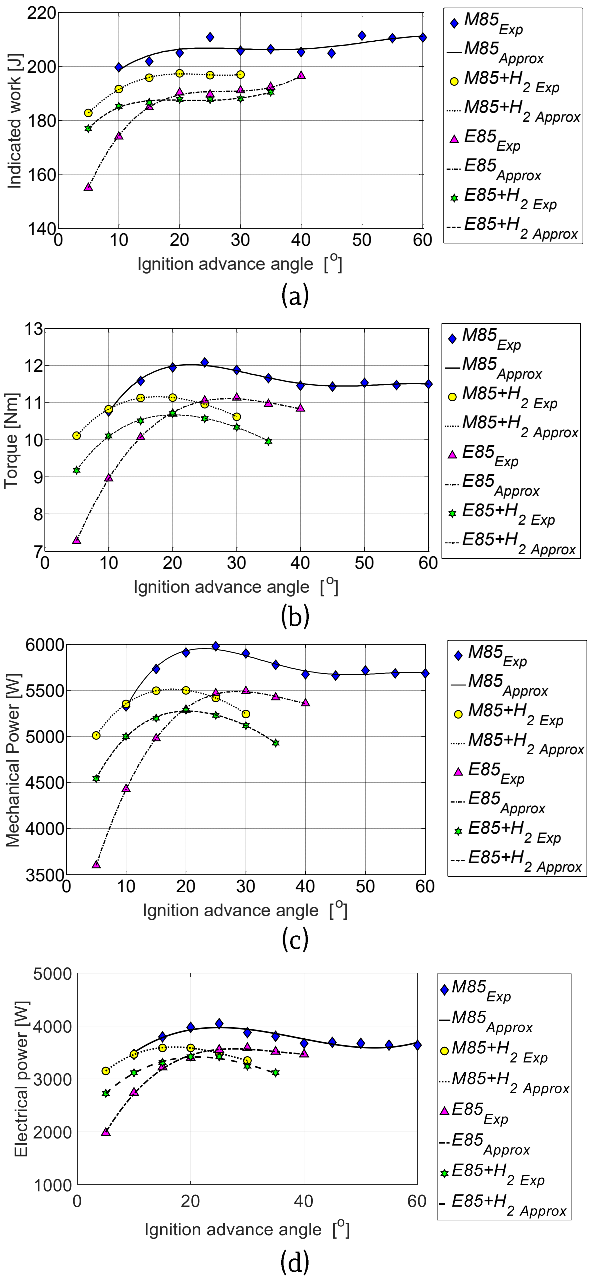

Figure 7: The graphs of (a) indicated work, (b) engine torque, (c) mechanical power, (d) electric power for four-stroke ICE for various IAA values

Figure 8a presents graphs of hydrocarbon HC emission. Figure 8b presents nitrous oxides Nox emission. Both figures show results for the ICE fueled by M85, M85+H2, E85, and E85+H2.

The highest hydrocarbon emission (Figure 8a) was obtained for E85 at IAA = 20˚, equal to 30 ppm. From the analysis of Figure 8b, the conclusion is that the NOx levels increased with higher IAA values. The highest NOx emission level (2693ppm) was measured for E85+H2 at IAA=35˚. At the same time, it should be noted that hydrogen addition has a positive effect - reduction of HC emissions. A 20% volumetric addition of hydrogen (E85+H2) reduces the emission of hydrocarbons when IAA is greater than 25˚. In the case of M85, the highest HC emission (18 ppm) was measured for IAA=25˚, and the highest NOx emission (1610 ppm) was measured for IAA=60˚. It should be emphasized that the 20% volumetric addition of hydrogen (M85+H2) positively affects the reduction of HC emissions (12 ppm for IAA=25˚).

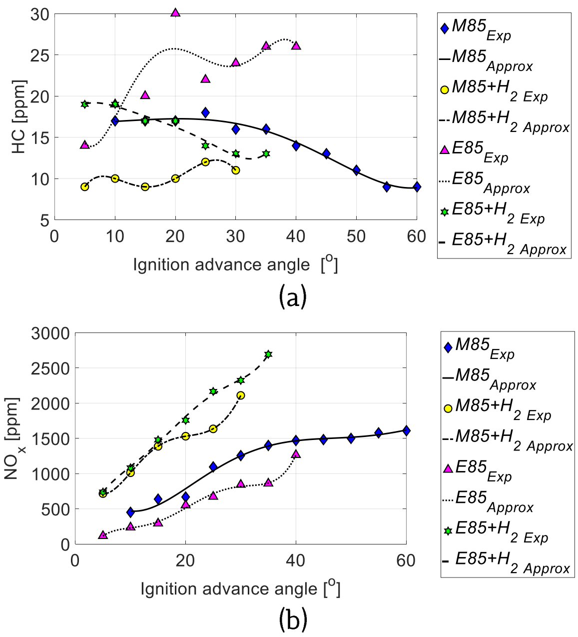

Figure 8: The effect of IAA on (a) HC emission and (b) NOx emission in exhaust gasses of the IEC powered with tested fuels

Summary

The experimental research demonstrates that increasing the ignition advance angle (IAA) up to

20°, while maintaining the engine's rotational speed at 4500 rpm, results in an increase in mean effective indicated pressure (MEIP) inside the cylinder, indicated work, mechanical power, torque, and electrical power, for the tested fuels. Furthermore, the addition of hydrogen to the considered fuels (M85 and E85):

- reduces hydrocarbon emissions in the exhaust system (positive outcome).
- increases NOx emissions (increased NOx emission) by lowering exhaust gas exhaust temperature (negative outcome).

It should be emphasized that the addition of hydrogen limits the possibility of controlling the ignition timing; as the volume of hydrogen increases, the IAA change control option decreases; for pure hydrogen, the maximum IAA value does not exceed 22.5° (value determined based on initial tests for $\lambda = 1.2$).

Based on the conducted tests, it was found that the best fuel for further usage is M85 without the addition of hydrogen. For the M85, the highest values of torque, mechanical power, electric power, indicated pressure and indicated work were obtained. The research highlights that while hydrogen-enhanced fuels offer environmental benefits in terms of reduced HC emission, their higher NOx emissions and moderate impact on engine performance suggest the need for further optimization of dual-fuel systems. Specifically, advanced combustion strategies, such as exhaust gas recirculation (EGR) or variable valve timing (VVT), could be explored to balance emissions and performance.

The authors' next research will focus on estimating the effective operating parameters of an ICE driven by alternative fuels using simulation models. These models could provide insights into optimizing hydrogen-fueled engines for broader applications in distributed energy systems and the hydrogen economy.

Acknowledgments

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