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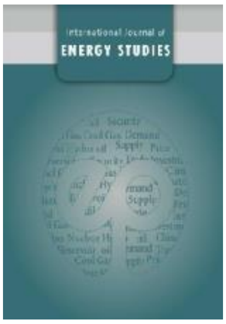

Research Article

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Performance and emission prediction of hydrogen addition to natural gas powered engine using 0/1 dimensional thermodynamic simulation

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Highlights

- BP, BTE and BSFC improved with increasing hydrogen addition.
- Despite the high compression ratio, no knocking was observed with hydrogen addition up to 5%.
- High compression ratio increased NO_X and CO emission values.

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ABSTRACT

With the increase in global warming, the measures taken by the governments regarding the use of internal combustion engines are also increasing. These measures, on the other hand, encourage the use of alternative fuels, both to reduce emissions and to research less use of petroleum-based fuels such as diesel and gasoline. Natural gas is one of the fuels that has been researched and used as an alternative fuel recently. However, the lower lean limit, high coefficient of variation (COV) of indicated mean effective pressure (IMEP), relatively lower diffusivity, requirement of high ignition energy and high flme quenching distance properties of natural gas compared to gasoline fuel have a limiting effect. However, these properties can be improved with the addition of a certain amount of hydrogen. In this study, a 3-cylinder diesel tractor engine was converted into a spark-ignition engine using natural gas. Then, by adding hydrogen at low rates between 1% and 5% by mass, its effects on performance, combustion characteristics, and emission values were examined. Despite the high compression ratio of the diesel engine, such as 17.5:1, it was observed that the addition of 5% hydrogen did not cause knocking. In addition, brake power (BP), brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), and brake mean effective pressure (BMEP) values improved with increasing hydrogen addition as 11.33%, 7.5%, and 0.49% respectively. In addition, in-cylinder temperature and pressure values increased due to increasing lower heating values and flame speed. While total hydrocarbon (THC) emission values decreased, nitrogen oxide (NOX) and carbon monoxide (CO) emission values increased slightly.

Keywords: *Natural gas, Hydrogen addition, Internal combustion engine, Performance, Emission.*

1. INTRODUCTION

Researches predict that internal combustion engines will continue to be used as the main power source, especially in the transportation sector [1,2]. However, the use of diesel and gasoline in internal combustion engines is gradually banned with the aim of "zero emission" [3]. These prohibitions, on the other hand, cause an increase in studies on the use of alternative fuels in existing or to be-produced internal combustion engines. In alternative fuel studies, besides biofuels, gaseous fuels such as natural gas, syngas, biogas, and hydrogen are used. With the use of these gaseous fuels, the dependency on petroleum-based fuels can be reduced by reducing engine emissions [4]. Among these alternative gaseous fuels, natural gas is one of the most remarkable ones. The advantages of using natural gas are that the extraction technology is advanced, its availability is abundant, the number of stations increasing around the world, the emission of emissions is lower than petroleum-based fuels, and its prices are cheaper [5]. In addition, according to the predicted values, the rate of vehicles working with NG in the USA until 2025 will be approximately 20% of the total heavy-duty vehicles [6]. It is seen that the use of natural gas has increased in recent years compared to petroleum-based fuels [7].

Besides its commercial advantages, natural gas also has some disadvantages. These include lower burning speed, narrow flammability range, lower calorific value, higher ignition energy, and higher quenching distance. These properties can be improved by the addition of hydrogen. By adding hydrogen to a certain extent, both the advanced properties of hydrogen and natural gas can be benefited from. With the addition of hydrogen, quenching distances decrease, a lower carbon to hydrogen (C/H) ratio is obtained, combustion performance improves and HC and CO emission values decrease. It also improves lean combustion, thereby reducing NO_X emissions [8].

By removing the injector of the diesel engine and replacing it with a spark plug, the fuel-air mixture can reach the combustion chamber homogeneously, preventing the formation of rich fuel regions and bringing the formation of soot to negligible levels [9-13]. In addition, thanks to the high compression ratio of the converted engine and the ability to burn with a leaner mixture, it can reduce emissions by increasing the combustion efficiency by providing higher turbulence formation compared to a gasoline engine [14].

When the literature studies are examined, it is seen that the studies on the conversion of an existing diesel engine to work with natural gas are generally carried out at low and medium loads for a compression ratio of 13.3:1 and less [15-17]. These studies, on the other hand, are mostly experimental and the effects of natural gas usage on in-cylinder combustion characteristics in a diesel engine converted without any change in the combustion chamber have been investigated. The effects of many parameters such as fuel-air ratio, spark plug ignition time, natural gas methane number were investigated. After the conversion, they concluded that the changes between cycles are low, stable combustion conditions are realized and knocking does not exceed the limit values. In general, the fuel equivalence ratio was studied between 1 and 0.71. With the decrease of the fuel equivalence ratio, the in-cylinder heat release and the resulting indicated power and thermal efficiency also decreased. However, while the ignition delay time increased, the combustion time increased to a certain extent and then decreased. In their study, Agarwal and Hora observed that with the addition of hydrogen to the engine with a 12:1 compression ratio working with natural gas, the engine torque and performance increased while the emission values decreased. In addition, BTE increased, BSFC decreased and combustion stability increased. In general, the combustion pressure increased with increasing hydrogen ratio. While HC, CO, and CO_2 emission values decreased at constant BMEP value, NO_X value increased. As a result, they found that a mixture of 30% hydrogen and 70% natural gas by volume was optimum [8]. Rao et al. investigated the effects of hydrogen addition at different rates at 25%, 50%, and 75% loads on an engine with a 12.1:1 compression ratio on performance and emissions for different EGR ratios and spark plug ignition times. As a result, 10% hydrogen and 10% EGR at low load, 50% hydrogen and 14% EGR at medium load, 50% hydrogen and 26% EGR at high load were found as optimum conditions [18]. Xu et al. investigated the effects of using natural gas and natural gas with hydrogen addition on performance and emission values in an engine with a compression ratio of 10.2:1. As a result, the maximum pressure and heat release rate increased with the addition of hydrogen. In addition, while NO_X emission increased, HC and CO emission values decreased. BSFC value also decreased [19]. In other literature studies examined, it was observed that the compression ratio was below 12.0:1 in general and performance improvement was observed according to the amount of hydrogen added. While NO_X emissions increased with increasing temperatures, HC and CO emissions generally decreased [20-22].

In the study, the effects of working with natural gas and natural gas-hydrogen mixtures of a tractor engine with a high compression ratio of 17.5:1 on the performance and emission values were investigated by using a 0/1-dimensional combustion program. Analyzes were performed under full load, at 2300 rpm, and for low hydrogen additions.

2. 0/1 DIMENSIONAL ENGINE MODEL

The AVL Boost program, which diagram is given in Figure 1, was used to examine the effects of hydrogen addition at different rates on performance, in-cylinder combustion, and emission values in a spark-ignition engine using natural gas in 0/1 dimensions. All engine components are modeled in the program, and the initial conditions and boundary conditions values closest to reality are defined [12, 23].

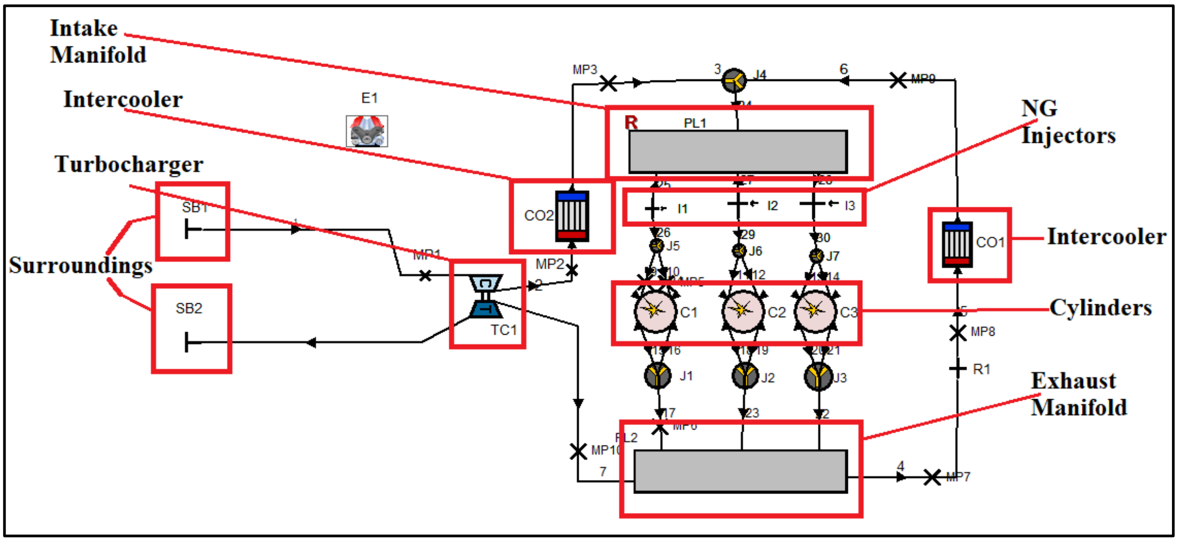

Figure 1. Image of engine components in the AVL Boost program

Basically, the Vibe 2-Zone combustion model and the Woschni 1978 heat transfer model were used in the program. The engine specifications used are given in Table 1.

Table 1. Engine Specifications

Specification	Value
Displaced volume - total (cm^3)	2930
Number of cylinders	3
Bore / Stroke (mm)	104 / 115
Compression ratio (-)	17.5:1
Injection system	Port fuel injection
Valve Time (° CA)	IVO: 28 bTDC
	IVC: 60 aBDC
	EVO: 65 bBDC
	EVC: 33 aTDC

The AVL Boost program provides 0/1 dimensional solutions to problems modeled on the basis of gas dynamics equations. This means that the temperatures, pressures and flow rates obtained from the solutions of the equations represent the average values in the cross-sections of the pipes. In addition, realistic solutions have been defined in order to minimize the losses caused by three-dimensional effects in any part of the engine, by determining the appropriate flow loss coefficients and reducing the margin of error. The continuity, momentum, energy, heat transfer, combustion and emission equations and theories used by the program to solve the defined conditions are given in detail in the relevant sources [12, 23-25].

In Table 2, the start of combustion time, air/fuel ratio, and fuel amount used in the program are given. As fuel, methane gas was used instead of natural gas, and the properties of methane and hydrogen used are given in Table 3.

Table 2. Engine Specifications

Parameter	**Value**
Engine speed (m/s)	2300 @ Full load
Start of Combustion (° CA ATDC)	0
Air/Fuel ratio (-)	26.8
Fuel mass (mg/st) (each cylinder)	64

Table 3. Hydrogen and natural gas properties [13, 26]

Properties	**Hydrogen**	**Natural Gas**
Main component	H Only	Methane (CH_4)
Auto-ignition Temperature (K)	858	923
Lower heating value (MJ/kg)	119.93	50
Density (kg/m^3)	0.08	692
Molecular weight (g/mol)	2.016	16.043
Flammability limits in air (vol %)	4-75	5-15
Flame velocity (m/s)	2.65-3.25	0.45
Specific gravity	0.091	0.55
Boiling point (K)	20.2	111.5
Cetane number	-	-
Octane number	130	120
CO_2 emissions (%)	0	9.5
Mass diffusivity in air (cm^2/s)	0.61	0.16
Min ignition energy (mJ)	0.02	0.28

3. RESULTS AND DISCUSSION

In the AVL Boost program, firstly, the diesel combustion model constructed in the diesel combustion regime was verified by comparing it with the experimental data [23]. Then, with the acceptance of installing a spark plug instead of a diesel injector, and a natural gas fuel injector on the intake manifold, studies of the new spark-ignition model, which works entirely with natural gas and natural gas-hydrogen mixture, were carried out. Analyzes were performed at 2300 rpm, under full load. The effects of 5 different masses of hydrogen addition on engine performance, in-cylinder combustion characteristics, and emission behavior were investigated.

Figure 2 shows the effects of hydrogen addition on BP and BSFC values. The BP value increased linearly with the addition of hydrogen. With the addition of 5% hydrogen, approximately 11.33% improvement in BP was achieved. The reason for this is that the lower heating value of hydrogen is higher than that of methane. The decrease in BSFC with increasing hydrogen ratio indicates that at higher hydrogen additions, less amount of fuel is required to produce unit power and vice versa. With the addition of 5% hydrogen, an improvement in 7.5% BSFC was achieved.

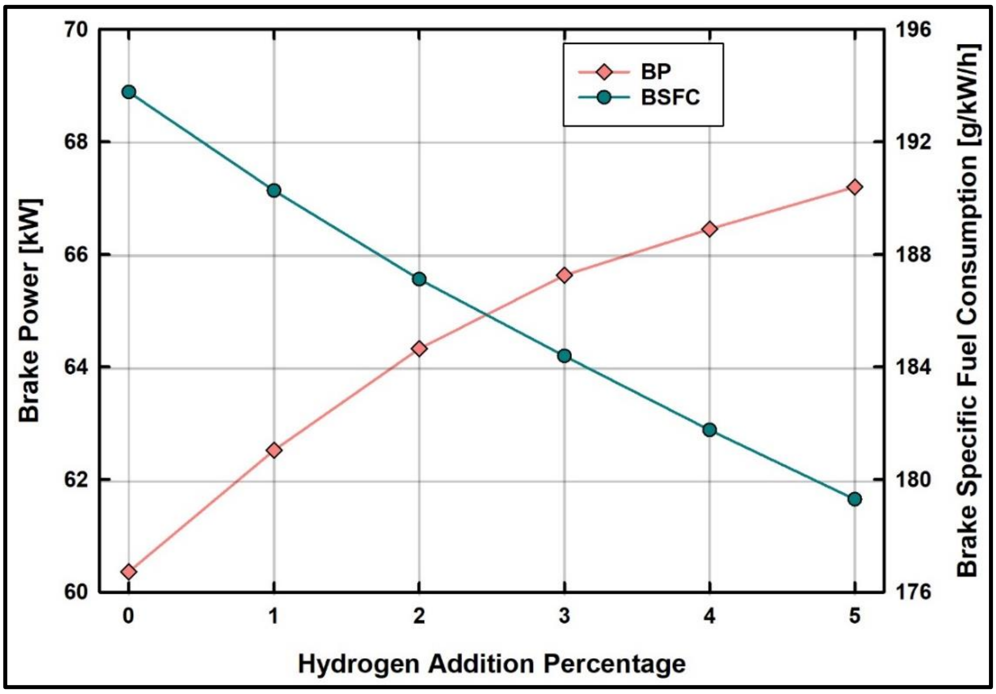

Figure 2. Brake power and brake specific fuel consumption change with hydrogen addition

Figure 3 shows the effect of hydrogen addition at different rates on BMEP, BTE, and MPRR ratios. BTE indicates the overall conversion efficiency of the chemical energy of the fuel into mechanical energy located in the engine shaft. Natural gas showed lower brake thermal efficiency compared to hydrogen mixtures. However, after 2% hydrogen addition, BTE remained constant and the difference was 0.49%. The reason why there is no significant increase in thermal efficiency despite increasing BP can be shown as the high lower heating value of hydrogen. The maximum BTE was determined as 36.9%. The BMEP value, on the other hand, increased with the increasing power due to the high lower heating value of the added hydrogen. The increase in BMEP with the use of 5% hydrogen was determined as 11.36%. The MPRR value is often associated with knock and noise and is one of the important parameters in engine design and optimization. This ratio is generally 1.5-1.0 MPa/Degree [10, 23] in the literature and is defined as the critical knock limit. The lower auto-ignition temperature and high flame velocity of hydrogen, on the other hand, increased the MPRR values with the addition of hydrogen. However, even with the addition of 5% hydrogen, it remained below the minimum knock limit value of 1.0 MPa/Degree. This showed that a diesel engine with a high compression ratio can run on methane and can safely add 5% hydrogen.

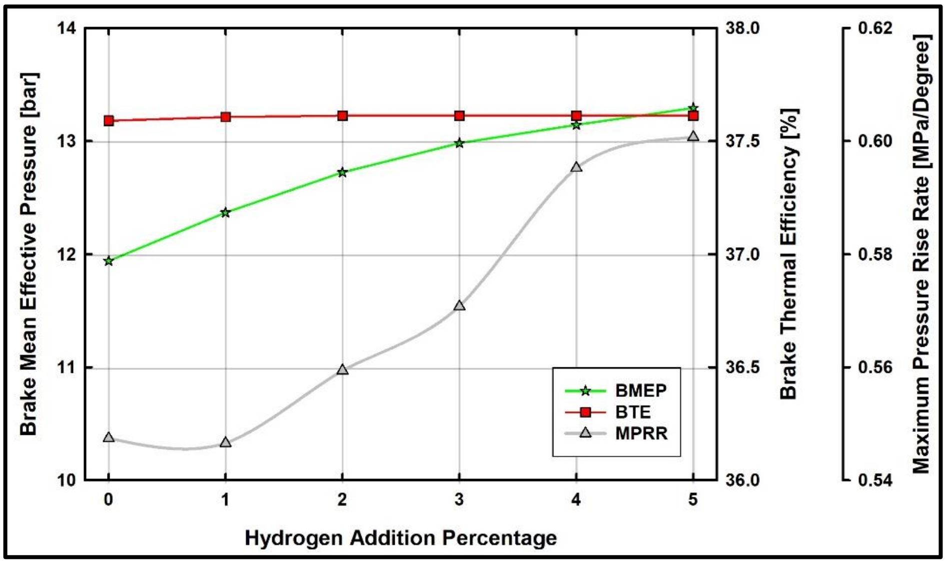

Figure 3. Brake mean effective pressure, brake thermal efficiency and maximum pressure rise rate change with hydrogen addition

Figure 4 shows the effects of hydrogen addition on the formation of maximum pressure and temperature in the cylinder. The lower heating value of hydrogen and the high flame speed caused the maximum in-cylinder pressure and temperature values to increase. The rate of increase in in-cylinder pressure and temperature was 4.27% and 4.91%.

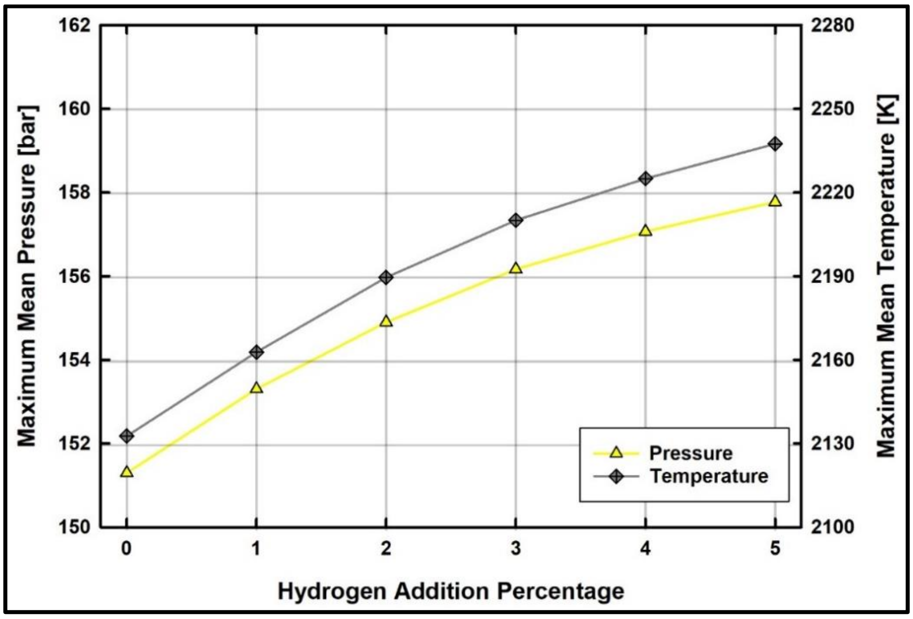

Figure 4. Maximum mean pressure and maximum mean temperature change with hydrogen addition

In Figure 5, the in-cylinder pressure variation of hydrogen addition at different rates is given. With the increasing hydrogen ratio, in-cylinder pressure values also increased depending on the high lower heating value and the flame velocity. However, with the increase in hydrogen ratio, the crank angle value at which the expected maximum pressure occurred did not come to the advanced. This is thought to be due to the low levels of hydrogen added and the combustion model used. The maximum in-cylinder pressure value was obtained as 157.7 bar at 730 crank angle.

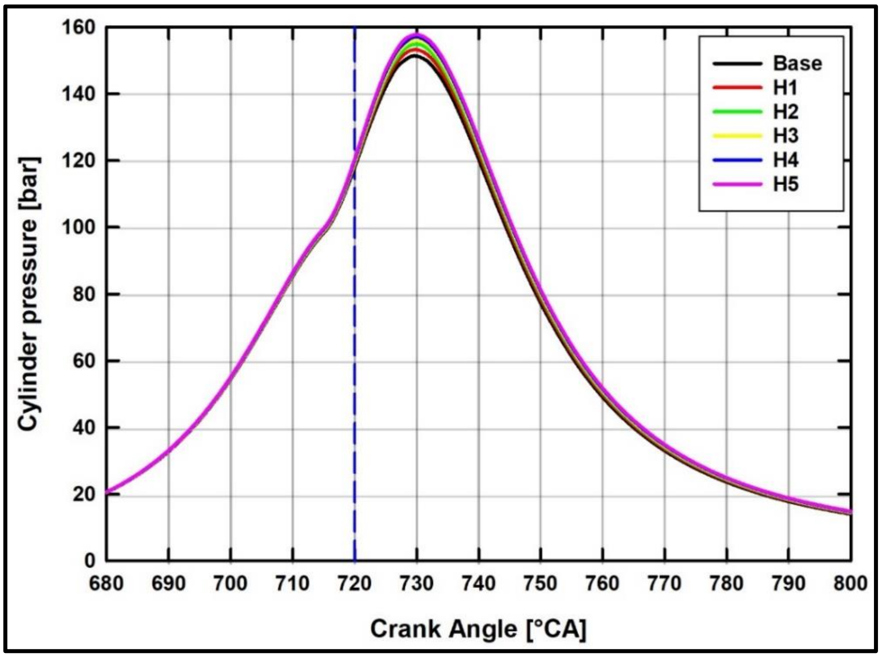

Figure 5. In-cylinder pressure change with hydrogen addition

In Figure 6, the variation of the in-cylinder heat release values of hydrogen addition at different rates is given. It was observed that the amount of heat release and its maximum value increased with increasing hydrogen addition. With the higher flame velocity and lower heating value, the sudden in-cylinder pressure formation and the maximum pressure value increased, resulting in an increase in the in-cylinder heat release values. The increase in the in-cylinder HRR value was 9.64% at 5% hydrogen addition and the maximum HRR value was 164.8 J/deg at 726 crank angle degrees.

In Figure 7, the effects of hydrogen addition at different rates on the in-cylinder temperature values are given. It was observed that the maximum in-cylinder temperature values increased with increasing hydrogen amount. With the addition of hydrogen, the increase in the total lower heating value of the fuel mixture and the in-cylinder flame temperature caused this increase. While the maximum temperature increase was 4.92%, the maximum in-cylinder temperature was 2237 K at 740 crank angle.

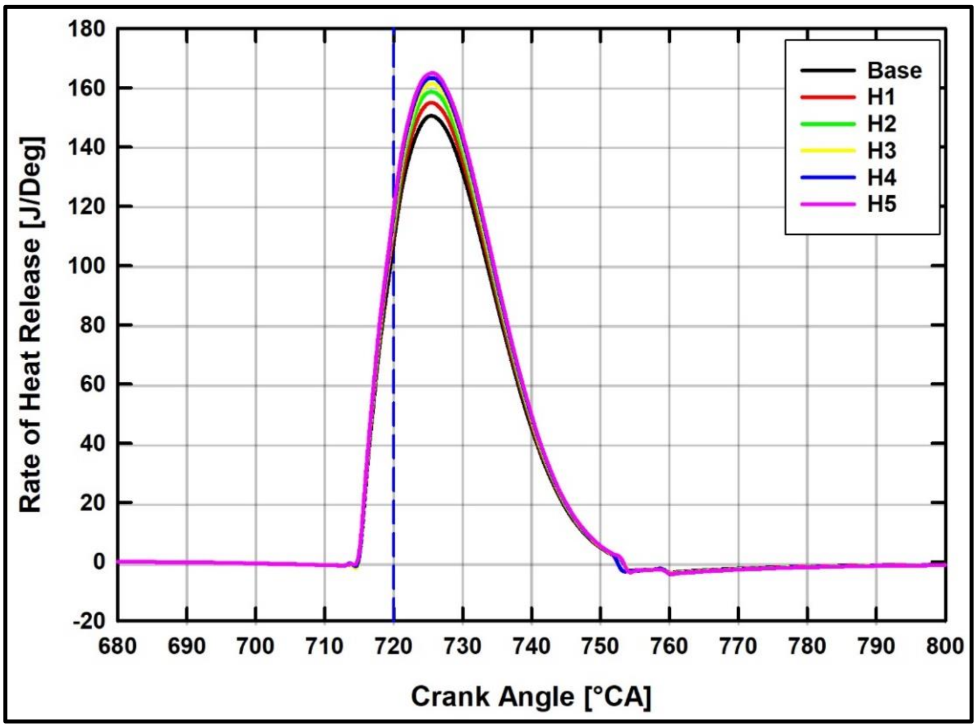

Figure 6. In-cylinder heat release rate change with hydrogen addition

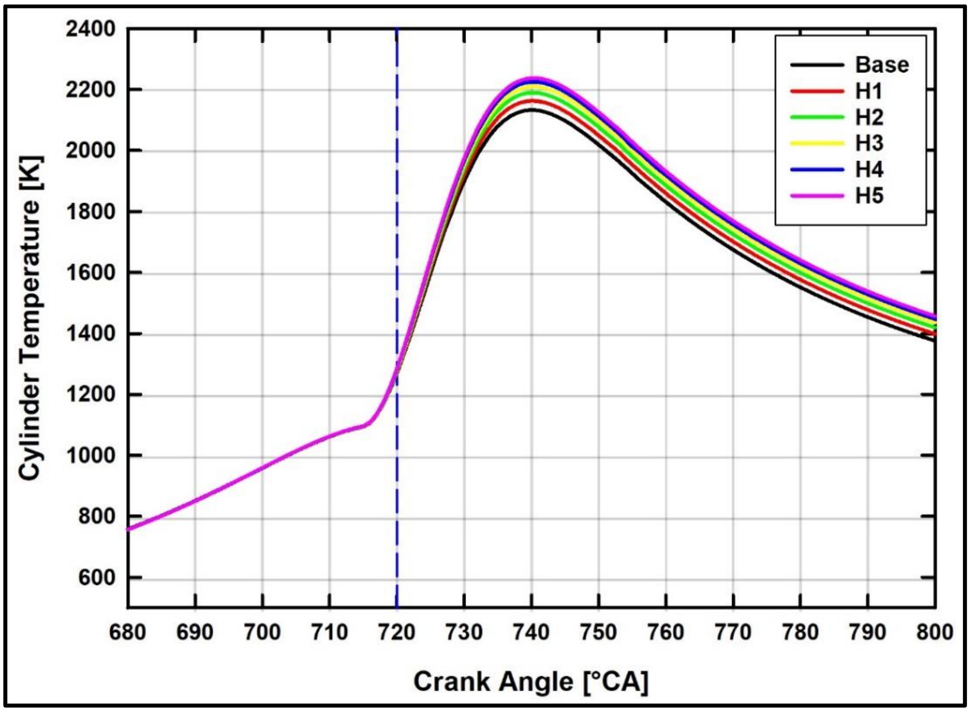

Figure 7. In-cylinder temperature change with hydrogen addition

In Figure 8, the effects of hydrogen addition at different rates on in-cylinder emission values are given. Emission values are given by normalizing according to the use of pure methane. According to the results obtained, with increasing hydrogen ratio, flame velocity and in-cylinder temperatures increased, and accordingly, in-cylinder NO_X values increased. It was observed that NO_X emission values increased 2.2 times with the addition of 5% hydrogen. HC emissions are directly related to combustion efficiency and in-cylinder temperature values. Increasing in-cylinder temperatures with the addition of hydrogen caused a decrease in THC emission values with the adsorption and oxidation of HC particles on the surface [27]. In addition, the high flame rate of hydrogen and sending methane and hydrogen as premixed fuel increased the combustion efficiency. The total hydrocarbon value decreased by 30% with the addition of 5% hydrogen. Since the CO emissions could not find the required O_2 for the combustion reaction, the conversion rate to CO_2 decreased and the CO emission values increased. The increase in CO emission value at the rate of 5% hydrogen was 21%.

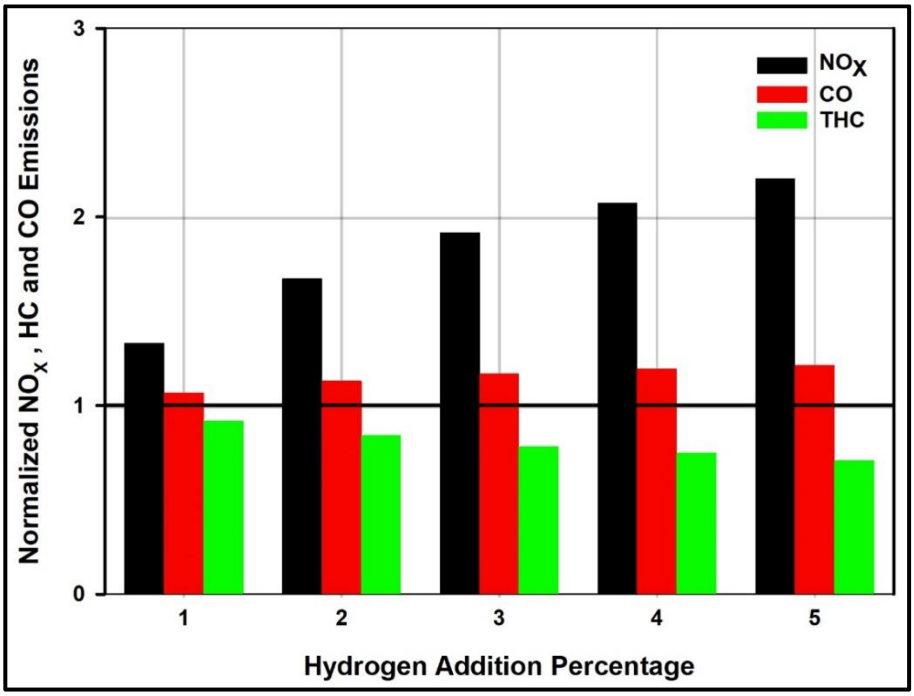

Figure 8. In-cylinder normalized emission change with hydrogen addition

4. CONCLUSION

The effects on engine performance, in-cylinder combustion characteristics and emission values as a result of hydrogen addition to a converted spark ignition engine using methane as the main fuel can be summarized as follows:

- In an engine with a high compression ratio of 17.5:1, it has been determined that adding 5% hydrogen is safe, especially when the MPRR value is taken as the limit.
- With the addition of hydrogen, engine performance values such as BP, BSFC, BTE, and BMEP have improved.
- With increasing hydrogen addition, maximum in-cylinder pressure and temperature values increased depending on flame velocity and lower heating values.
- Due to the increased in-cylinder temperature and insufficient O_2, NO_X and CO values increased, while THC values decreased.

In general, it is seen that the addition of up to 5% hydrogen has a positive effect on the performance of a converted engine with methane fuel spark ignition with a high compression ratio, while it has been concluded that it varies for emission values.

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DECLARATION OF ETHICAL STANDARDS

The author of the paper submitted declares that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHOR

Fatih Aktas: Performed the computations, analyzed the results and wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

NOMENCLATURE

BP	Brake power
BTE	Brake thermal efficiency
BSFC	Brake specific fuel consumption
NO_X	Nitrogen oxide
THC	Total hydrocarbon
CO	Carbon monoxide
COV	Coefficient of variation
IMEP	Indicated mean effective pressure
bTDC	Before top dead center
AbDC	After bottom dead center
bBDC	before bottom dead center
aTDC	After top dead center
mg	Miligram
st	Stroke

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