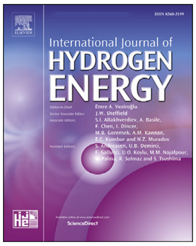
Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he



The effect of hydrogen addition to compressed natural gas on performance and emissions of a DI diesel engine by a numerical study

J. Zareei [a,*], *M. Haseeb* [b], *K. Ghadamkheir* [a], *S.A. Farkhondeh* [a], *A. Yazdani* [a], *K. Ershov* [c]

[a] *Department of Biosystems Engineering, Faculty of Agriculture, Ferdowsi University of Mashhad*
[b] *Taylors Business School, Taylors University Lakeside Campus Jalan Taylors Subang Jaya Selengor, Malaysia*
[c] *Department of Propaedeutics of Dental Diseases, Sechenov University, Moscow*

HIGHLIGHTS

- Effect of adding hydrogen to a CNG fuel on performance and exhaust emissions.
- Hydrogen addition is beneficial for converting the fuel's chemical energy into power.
- Engine performance increased with a higher fraction of 30% in HCNG mixtures in comparison to Pure Diesel and CNG.
- NOx emission increased with increase of hydrogen in HCNG but HC, and Soot emissions decreased.

ARTICLE INFO

Article history:
Received 7 June 2020
Received in revised form
1 September 2020
Accepted 4 September 2020
Available online xxx

Keywords:
Hydrogen
Natural gas
Emissions
Engine performance
Alternative fuel

ABSTRACT

Diesel engines are the most commonly used internal-combustion engines. Due to incomplete combustion of fossil fuels, engine performance and emissions output are unsuitable. On the other hand Emissions of greenhouse gases using fossil fuels in internal-combustion engines are considered to be the main cause of climate change. Thus to find an alternative fuel to eliminate or reduce CO_2 and exhaust emissions is an urgent concern worldwide. Superabundant and readily available, makes hydrogen an attractive alternative to fossil fuels. In this study, a 3-cylinder turbocharged diesel engine is converted into CNG direct-injection engine and then hydrogen as a fuel enrichment added to CNG. AVL Fire™ Software is used to simulate the engine at different engine speeds, injection pressure, and Air/Fuel ratios. The results confirm that adding hydrogen to CNG improves brake thermal efficiency and engine brake power, reduces brake specific fuel consumption as well as the diminution in HC and Soot but also increases the NO_x.

Introduction

Following the 1970s Arab oil embargo against the west, rendering a sharp increase in oil prices, fuel consumption

---

* *Corresponding author.*
E-mail address: javadzareei@um.ac.ir (J. Zareei).

https://doi.org/10.1016/j.ijhydene.2020.09.027

Please cite this article as: Zareei J et al., The effect of hydrogen addition to compressed natural gas on performance and emissions of a DI diesel engine by a numerical study, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.09.027

Nomenclature

A/F	Air/Fuel
ATDC	After top dead center
BP	British petroleum
BSEC	Brake specific energy consumption
BMEP	Brake mean effective pressure
BTDC	Before top dead center
CA	Crank angle
CFD	Computational fluid dynamics
CHR	Cumulative heat release
CO	Carbon dioxide
CAD	Crank angle degree
CO_2	Carbon monoxide
CNG	Compressed natural gas
EGR	Exhaust gas recirculation
EGT	Exhaust gas temperature
GHG	Greenhouse emissions
HC	Hydrocarbon
HCNG	Hydrogen-CNG
HRR	Heat release rate
IC	Internal combustion
IMEP	Indicated mean effective pressure
LHV	Lower heating value
NG	Natural gas
RMSE	Root mean square error
SSE	Sum of squared estimate of errors
SFC	Specific fuel consumption
SI	Spark ignition
SVM	Support vector machine
TBTE	Torque brake thermal efficiency
THC	Total unburned hydrocarbons

becomes a major concern for the transport and automotive industry. In particular, necessitating more efficient engines and high-quality fuel, due to strict regulation imposed by states to meet "the Paris Agreement" objectives further exacerbated the need for alternative fuels [1,2]. NG mostly consists of 98.3% Methane (CH_4) and is a premium alternative but according to the BP statistical review of world energy 2019, there are about 196.9 trillion Cubic meters proven NG at the end of 2018 [3,4].

Methane produced less CO_2 in comparison to gasoline (Octane C_8H_{18}) and diesel ($C_{12}H_{23}$) since the ratio of carbon to Hydrogen is 1–4 compared to 8 to 18, and 12 to 23, hence natural gas has the least carbonyl emissions among other (fossil) fuels [5,6]. Anti-knocking property due to higher amounts of auto-ignition temperature and octane number, while having high thermal efficiency makes natural gas a beneficial fuel in terms of engineering application [7,8]. But also Methane is a greenhouse gas, and its leakage and unburned form is harmful [9]. Hydrogen can improve some of the combustion characteristics and reduce greenhouse emissions of natural gas [10]. Furthermore, it can be produced from surrounding resources. But the main disadvantages for hydrogen (to be used in diesel cycle engines) are high auto-ignition temperature, long auto-ignition delay, and high rate of the pressure rise. Nevertheless, high diffusivity, high calorific value, flame speed, and short quenching distance are the main reasons for hydrogen to be blended with various fuels [11–13].

Extensive researches are working on the effect of hydrogen addition to other fuels on engine's efficiency, emissions and fuel economy. Studying the effect of the compression ratio on an engine fueled by HCNG blends showed that hydrogen addition to fuel would increase maximum cylinder pressure. Also, thermal efficiency improved by increasing the compression ratio. The inclusion of hydrogen in the blend reduces CO_2 [14] and is an effective method for the reduction of harmful emissions below the EURO IV standards requirements [15–17]. Engines using hydrogen can be run on lean mixtures because of the low amount of ignition energy which hydrogen needs (approximately 0.02 mJ) [18,19]. Results of a comparative study between emissions and performance between engines with various fuels also including CNG and HCNG proved that HCNG has a lower amount of all emissions except NOx than CNG. In addition, a reduction in unregulated carbonyl emissions (expect for Methanol, Ethanol, Formaldehyde, nitrogen dioxide, and Acetaldehyde) and enhancement in engine's specific fuel consumption occurs in case of adding hydrogen to CNG [20,21].

Combustion, vibration and noise analysis of an engine fueled with hydrogen-diesel investigated by Nag et al. (2019) [22] and the results showed that in lower engine loads, knocking tendency decreases and vibrations are quite moderate by hydrogen addition but at high loads knocking, and vibrations increased, also the addition of hydrogen to diesel would decrease SFC, CO_2, CO, and increases the brake thermal efficiency [23]. Studying emissions and combustion characteristics of an engine at different NG-H_2 blends at various engine loads resulted in a significant increase in peak pressure, heat release. Hydrogen addition to natural gas is a very beneficial method for diminishing engine HC, CO, CO_2, and Soot, especially at high engine loads, improving fuel economy with decreasing BSEC [24–26]. But the amount of NO_x increased by using this blend as the fuel [27–30]. Investigations prove that hydrogen addition to diesel would have a positive impact on engine power output, mean effective pressure, also CO and smoke emissions, While because of the knocking phenomenon Brake Thermal efficiency would be limited [31,32]. Hydrogen-diesel dilution by Nitrogen (N_2) in a turbocharged IC Engine with EGR would increase the IMEP, also an effective method for NO_x reduction. Furthermore, by a high fuel-air equivalence ratio, HC and CO decrease significantly. Also, have positive effects on the engine knock and provide a better thermal efficiency [33,34]. Instead of just using the fresh air in the combustion chamber, mixing hydrogen with fresh air in (intake) manifold and the chemical reaction between the mixture and diesel, as injected fuel it would increase the amount of TBTE and reduce SFC, HC, CO, and CO_2. In this condition, the amounts of NO_x would increase, but if the engine is equipped with EGR this emission can be reduced significantly [35,36]. In addition to passenger cars, hydrogen can be used as an alternative fuel in the marine industry Based on researches accomplished by Deniz, Zincir (2015), merchant ships can use hydrogen as an alternative fuel, which shows better characteristics in comparison to LNG

Please cite this article as: Zareei J et al., The effect of hydrogen addition to compressed natural gas on performance and emissions of a DI diesel engine by a numerical study, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.09.027

fuel as well as simpler fuel supply system components and rendering the least investment costs [37]. Performances of a heavy-duty engine with HCNG fuel (with 18% of hydrogen content), were investigated and as the results showed, due to the great effect of H_2 on fuel spray combustion, hydrogen addition to CNG would enhance the engine performance in vehicles and also better engine power achieved. The effect of hydrogen addition is positive on the reduction of THC, CH_4, and CO but also negative for the increasing amount of NO_x, which can be reduced by using effective pre-intake, in-cylinder, and post-combustion control strategies [38–40]. Also in similar researches for SI engines using HCNG as the fuel, effect of ignition timing on an engine with HCNG fuel shows that if the time interval between the end of fuel injection and the ignition start decreases, the BMEP and effective thermal efficiency would be increased. In a specific ignition timing adding hydrogen to CNG would decrease the combustion duration, also with optimal spark timing and EGR rate a reduction in NO_x occurs without negative effects on HC and CO, further improvement in combustion acceleration by adding hydrogen to CNG indicated fewer spark timing advances needed for efficiency enhancement [41,42]. In HCNG fueled engines, retardation of ignition timing is a good option for reducing CO, which can also be decreased by increasing lambda (Air-fuel mass ratio) and Manifold Absolute Pressure [43,44]. Also, a study by Rocha et al. concluded that the addition of hydrogen to biodiesel would increase NOx, due to the high temperature of hydrogen combustion and decreases CO, CO_2, and HC [45]. Similarly, a study by Kalsi et al. (2017) [46] shows that using HCNG on a biodiesel fueled engine NO_x emission increased marginally with HCNG however it is still less than base biodiesel. Parthasarathy et al. (2016) [47] studied the effect of adding hydrogen to biodiesel-ethanol blend and the results showed that using the blend with hydrogen would reduce NO_x and CO, Specific energy consumption. But the peak pressure increased in full load condition, and brake thermal efficiency improved in comparison to neat diesel. Also, an investigation on Engine performance and emissions using bio gas-hydrogen blends on a diesel engine in dual fuel mode by Deheri et al. (2020) [48] shows a deterioration in HC and CO, BTE, EGT, and BSFC. Also, amounts of peak cylinder pressure and HRR increased while NO_x and smoke emissions decreased significantly.

Today, one of the biggest challenges humanity faces is how to reduce environmental pollution, which has a negative impact on the lives of living creatures and the climate. One of the most important causes of these pollutants is the emissions from fuel combustion. The purpose of this paper is to find an alternative fuel for diesel engines that not only reduces pollution but also improves engine performance. In this regard, the engine performance and exhaust emissions in a 3-cylinder four-stroke engine, with changing diesel fuel to HCNG in different volumetric percentages of hydrogen in the blend of HCNG studied. Also, the pressure injection, air/fuel ratio, and the percentage of hydrogen enrichment changed at different engine speeds. In-cylinder pressure, specific fuel consumption, brake power, brake thermal efficiency as well as regulated gas emissions (Soot, NO_x, and HC) were mainly obtained and analyzed by using AVL Fire™ software.

Materials and methods

Numerical setup

In another study by Zareei, Rohani (2020) [49], the SVM model was used to estimate different parameters of an engine fueled with HCNG, and the optimal amount of hydrogen used in the blend was between 20 and 30%. In this work, the 3-cylinder diesel engine simulated by AVL Fire™ software to study the effect of injection pressure and Air/Fuel ratio and also hydrogen enrichment to CNG on performance and engine exhaust emissions. As shown in Fig. 1 typical CNGDI engine with a single cylinder and two exhaust and intake valves is used. For the analysis of heat transfer and turbulence characteristics and preparation of fuel mixing for the subsequent best combustion process, the three places for direct injection fuel injectors were examined and the best place considered for in this study. Therefore, the below model is designed using CATIA software and after sketching the geometry of the CNGDI engine, the Gambit software used for mesh generation. Fig. 2 shows the final model after grid generation, which is prepared to be simulated in AVL Fire™.

In this research, a simulation done for HCNG blends with different fractions of H_2 concentration (from 0% to 40% hydrogen volumetric content in the mixture) and also pure diesel for a DI engine which its detailed specifications are shown in Table 2. The AVL CFD solver is based on the Finite volume method, which has the ability to use any unstructured grids consists of polyhedral calculation volumes, in order to solve the PEDs in the form of algebraic equations [50,51]. The numerical methods and the activated submodels in this CFD simulation are summarized in Table 1.

Model verification

In this work, the simulation of the engine's performance, combustion, and emissions for different hydrogen enrichments in the HCNG blend, CNG, and diesel fuel were done by AVL Fire™ software. But in order to prove that the obtained results are reliable, validation is necessary. A data validation

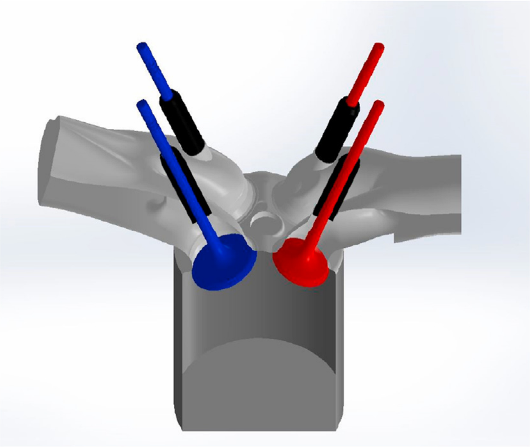


Fig. 1 – Schematic of the geometry of a CNGDI engine.

Please cite this article as: Zareei J et al., The effect of hydrogen addition to compressed natural gas on performance and emissions of a DI diesel engine by a numerical study, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.09.027

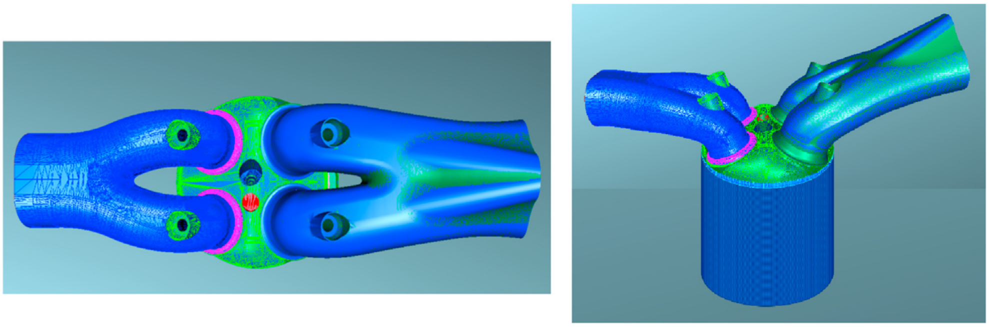


Fig. 2 – Schematic view of the computational engine domain.

Table 1 – Activated submodels.

Discretization algorithm	Simple/Piso
Turbulent model	k-ε model
Combustion model	Eddy break up model
NOx mechanism	Extended Zeldovich
Soot model	Kinetic model

Table 2 – Engine specifications.

Engine	Perkins 1103A-33TG1
Number of cylinder	3
Bore and Stroke (mm)	105 × 127
Compression Ratio	17:1
Displacement (L)	3.3
Maximum Power	47kw
Aspiration	Turbocharged
Combustion system	Indirect injection
Cycle	4 Stroke
Length (cm)	104
Number of nozzle holes	4
Fuel mass	5.2×10^{-6} kg
Nozzle hole diameter	0.0002 m
Start of injection	23° CA BTDC
End of injection	7° CA ATDC

between simulation results gained from AVL Fire™ and experimental data (achieved by Bose, Maji, 2009) [52], in engine brake thermal efficiency, compared. The difference between these two data was in the range of 1.84%–3.64% at 80% engine load, and for 20% engine load the difference was approximately between 1.71% and 4.1%. Values of SSE and RMSE that are two important criteria related to the goodness of validation are 0.2754 and 0.1856, respectively. Also, a linear regression between variables (shown in Fig. 3) with $R^2 = 0.99$ indicates a good coefficient of determination between variables. So it can be concluded that due to the satisfactoriness of the validated data, the generalization of other engine parameters captured by the software can be reliable.

In-cylinder flow modeling

Efficiency in IC engines is closely dependent on the quality of air and fuel mixing. The intensity of swirl and tumble in the cylinder is really important for the optimization of the mixture and engine efficiency similarly [53]. Continuity and momentum equations which describe the transient, incompressible, and turbulent flow requires the amount of turbulent viscosity for being solved. The k-ε model is the most widely used turbulence model, particularly for industrial computations. In this study, the k-ε two-equation turbulence model, which is very applicable in CFD simulations has been used, because it is numerically robust and has been tested in a broad variety of flows, including heat transfer, combustion, free surface and two-phase [54].

In this model, the amount of turbulent kinetic energy and the dissipation rate achieves from equations (1) and (2) respectively.

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right]+2\mu_t E_{ij}E_{ij}-\rho\varepsilon \tag{1}$$

$$\frac{\partial(\rho \varepsilon)}{\partial t}+\frac{\partial(\rho \varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t E_{ij}E_{ij}-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{2}$$

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon} \tag{3}$$

where, k is the turbulent kinetic energy, and ε is the dissipation rate. ρ is density, p is pressure, u_i is the velocity component in the corresponding direction, E_{ij} is component of the rate of deformation and μ_t is eddy viscosity. And also σ_k, σ_ε, C_μ, $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are the constants which their standard values are:

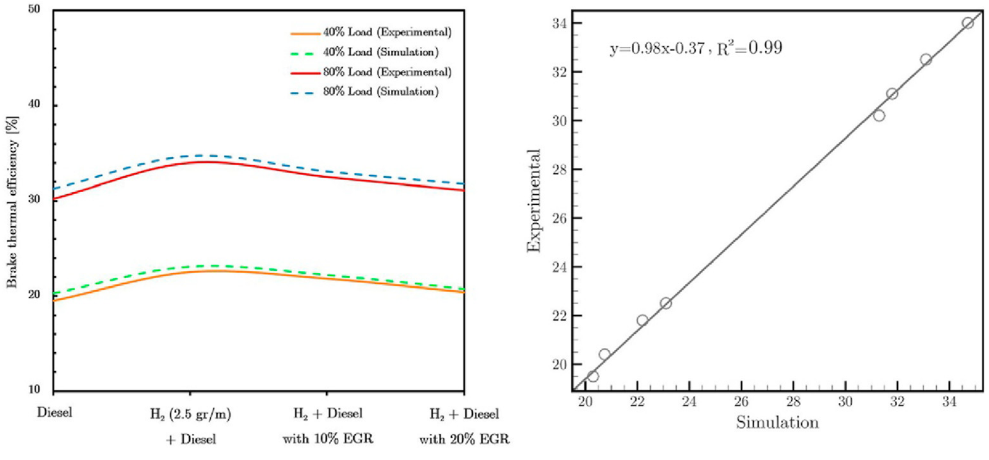
$$C_\mu = 0.09, C_{1\varepsilon} = 1.44, C_{2\varepsilon} = 1.92, \sigma_k = 1, \sigma_\varepsilon = 1.3, \sigma_\rho = 0.9. \tag{4}$$

As shown in eqn. (3), the turbulent viscosity can be calculated by having the amounts of variables k and ε. Consequently, the continuity and momentum equations can be solved to define flow behavior.

Pollutant formation models

In a study by Rao A et al. (2010) [55], 3 different NO_x prediction models were investigated and compared to each other. In this simulation, the reaction mechanism was expressed in terms of the extended Zeldovich mechanism. This mechanism considers 3 forward and backward reactions (shown in Eqs. (5)–(7)) of nitrogen oxides formation [56,57]. The reaction mechanism is known as the extended Zeldovich mechanism that considers the effect of oxygen, nitrogen, and hydrogen

Please cite this article as: Zareei J et al., The effect of hydrogen addition to compressed natural gas on performance and emissions of a DI diesel engine by a numerical study, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.09.027



(a) Difference between simulation and experimental results

(b) Linear regression between the experimental and simulation variables

Fig. 3 – The validation of simulation data.

Table 3 – Energy and Mass Composition of the H_2-CNG blend [59].

	0% HCNG	10% HCNG	20% HCNG	30% HCNG	40% HCNG
H_2 (% Mass)	0	1.21	2.69	4.52	6.72
H_2 (% energy)	0	3.09	6.68	10.49	15.59
LHV(MJ/kg)	46.28	47.17	48.26	49.61	51.41
LHV stoich. mixture (MJ/NM3)	3.376	3.359	3.353	3.349	3.344
CNG mass (mg)	5.2	5.13708	5.06012	4.96496	4.855
Hydrogen mass (mg)	0	0.06292	0.13988	0.23504	0.345

radicals on NO formation. Also, 10% as the EGR mass fraction applied in the initial condition of the CFD simulation, to reduce the combustion temperature and consequently, the amount of NO_x emitted from the engine.

$$O + N_2 \underset{k_{-1}}{\overset{k_1}{\leftrightarrow}} NO + N \tag{5}$$

$$N + O_2 \underset{k_{-2}}{\overset{k_2}{\leftrightarrow}} NO + O \tag{6}$$

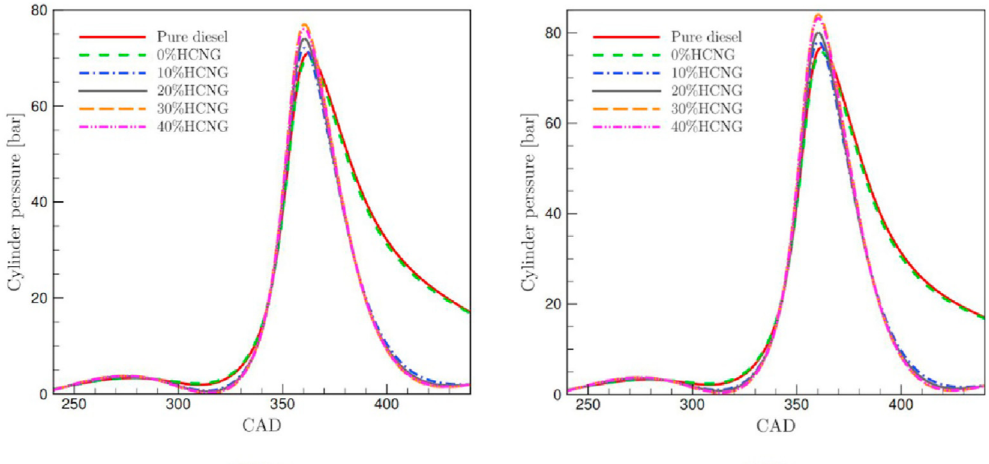
$$N + OH \underset{k_{-3}}{\overset{k_3}{\leftrightarrow}} NO + H \tag{7}$$

The net rate of NO formation is determined by the formation rate of NO from the three-step extended Zeldovich mechanism as below [58]:

$$\frac{d(NO)}{dt}[NO] = k_1[O][N2] - k_{-1}[NO][N] + k_2[N][O_2] - k_{-2}[NO][O] + k_3[N][OH] - k_{-3}[NO][H] \tag{8}$$

here, k_1, k_2, and k_3 are the reaction rate constants for the forward reactions and k_{-1}, k_{-2} and k_{-3} are for the reverse reactions.

Also, for calculating the amount of soot produced during the combustion of fuel, the Kinetic Soot Model used, which its basis is a detailed chemical reaction scheme for the calculation of soot formation and oxidation for different fuel classes.

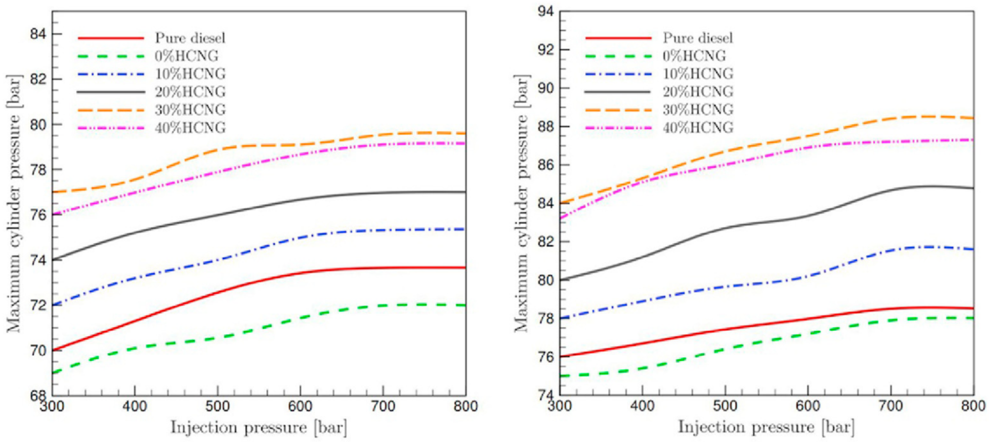


(a) 1200rpm

(b) 2400rpm

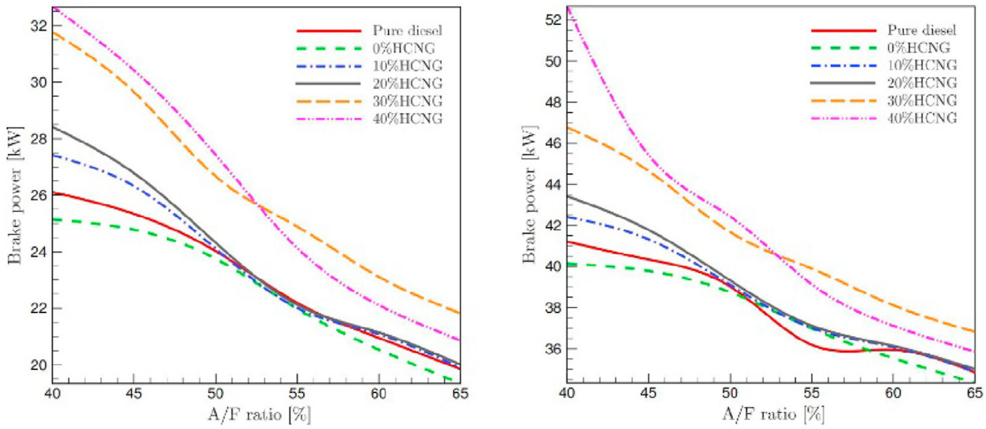
Fig. 4 – Variation of cylinder pressure with the crank angle at different hydrogen enrichment mixture percent at full load condition.

Please cite this article as: Zareei J et al., The effect of hydrogen addition to compressed natural gas on performance and emissions of a DI diesel engine by a numerical study, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.09.027

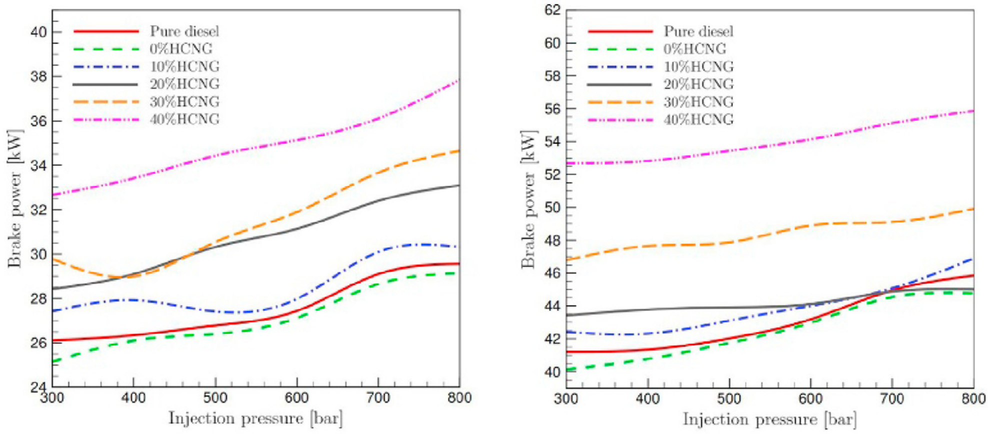


(a) 1200rpm (b) 2400rpm

Fig. 5 – Variation of Maximum cylinder pressure with injection pressures at different hydrogen enrichments and full load condition.



(a) 1200rpm (b) 2400rpm



(c) 1200rpm (d) 2400rpm

Fig. 6 – The amount of brake power with various A/F ratios and injection pressures.

Please cite this article as: Zareei J et al., The effect of hydrogen addition to compressed natural gas on performance and emissions of a DI diesel engine by a numerical study, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.09.027

Chemical reaction

The Chemical reaction of diesel, methane, and hydrogen with air in the stoichiometric condition is shown in Eqs. (9)–(11). As shown hydrogen would not produce CO_2, Therefore methane-hydrogen mixture produces less CO_2, which makes it a cleaner fuel than diesel. The overall chemical of the HCNG blend with different hydrogen volumetric concentrations is presented in Table 3.

$$4C_{12}H_{23} + 71O_2 \rightarrow 48CO_2 + 46H_2O \tag{9}$$

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 2 \times 3.76N_2 \tag{10}$$

$$H_2 + 0.5(O_2 + 3.76N_2) \rightarrow H_2O + 0.5 \times 3.76N_2 \tag{11}$$

Combustion modeling

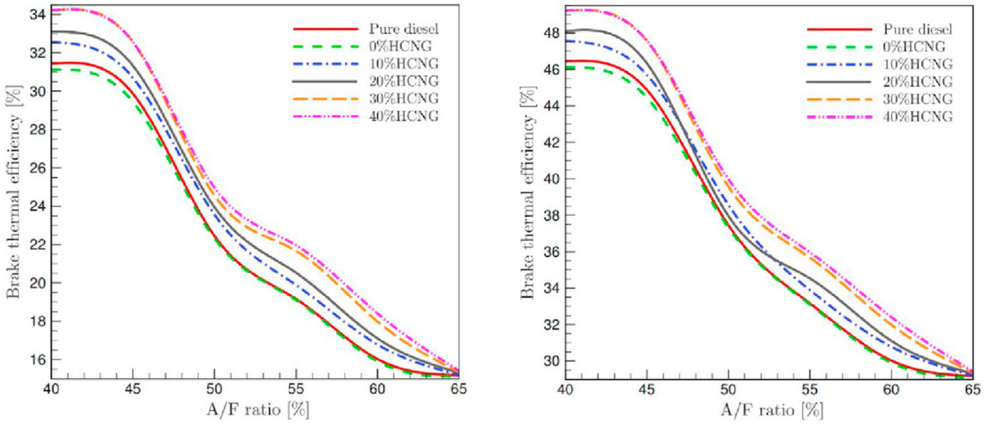
AVL Fire™ can simulate all kinds of premixed, partially premixed, and non-premixed combustion. In this research, the non-premixed combustion of Hydrogen-CNG blend with the intake air simulated with the Eddy break-up combustion model, this model is based on the assumption that the mean turbulent reaction rate is determined by the intermixing of cold reactants with hot combustion products. In this model, the rate of combustion is determined by the rate of intermixing on a molecular scale of eddies containing reactants and those containing hot products [60].

Results and discussion

The simulation results of Combustion characteristics, efficiency, and emissions for fuel with different hydrogen-CNG mixtures (0%, 10%, 20%, 30%, and 40% of hydrogen content in total HCNG) and also with pure diesel, at different engine speeds are shown in sub-sections below.

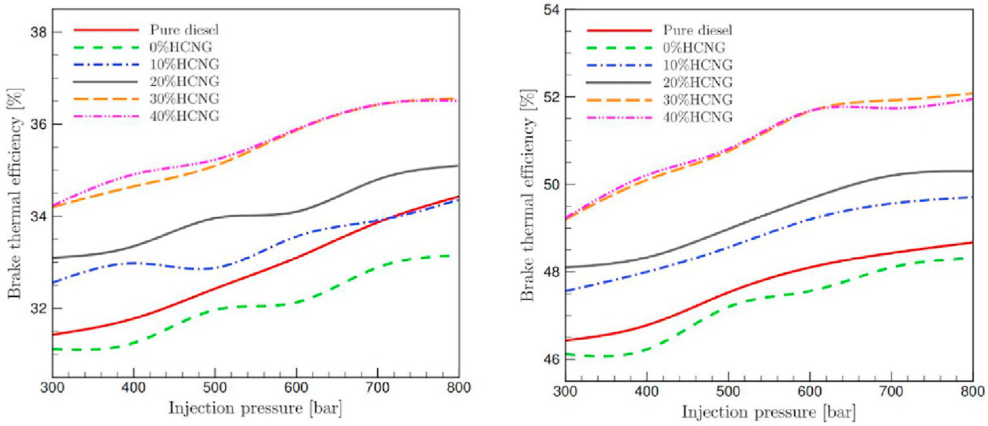
Cylinder pressure

Generally adding hydrogen to CNG will improve the engine's performance parameters. Fig. 4 shows the amount of cylinder pressure at two constant engine speeds with various HCNG blends and 40:1 of A/F ratio, as observed from the results from the simulation, by increasing the percentage of hydrogen in HCNG mixture the amount of cylinder pressure enhanced in



(a) 1200rpm

(b) 2400rpm



(c) 1200rpm

(d) 2400rpm

Fig. 7 – The amount of brake thermal efficiency with various A/F ratios and injection pressures.

Please cite this article as: Zareei J et al., The effect of hydrogen addition to compressed natural gas on performance and emissions of a DI diesel engine by a numerical study, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.09.027

comparison to pure diesel and CNG because of its early start of combustion, which causes a large amount of fuel burned in the combustion phase.

Comparing amounts of maximum cylinder pressure in different HCNG blends versus pure diesel at 1200 and 2400 rpm in various injection pressures and A/F ratios, it is inferred that higher values of Maximum cylinder pressure can be reached by increasing the amount of hydrogen content in HCNG (Fig. 5). By using HCNG with 30% of hydrogen content, in comparison to pure diesel, maximum cylinder pressure would be increased up to 5.94 bar and 9.91 bar at 1200 and 2400 rpm, respectively.

Engine brake power

As shown in Fig. 6 Engine brake power has been investigated with pure diesel, and different HCNG blends at two constant engine speeds (1200 and 2400 rpm), once with various A/F ratios and once with various injection pressures (with A/F ratio of 40:1). In comparison to pure diesel and CNG, brake power can be enhanced by increasing hydrogen concentration in the HCNG blend, along with higher injection pressure. Results show that in comparison to pure diesel, by blending 40% hydrogen with CNG, brake power would be increased up to 8.3 kW and 10.01 kW at 1200 and 2400 rpm, respectively.

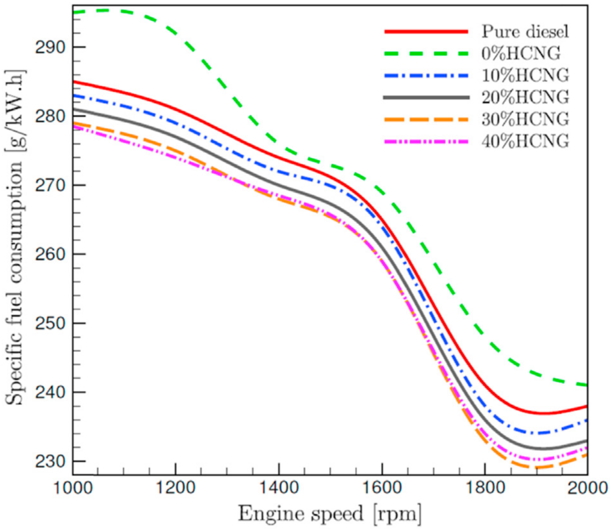


Fig. 8 – The amount of specific fuel consumption at different engine speeds.

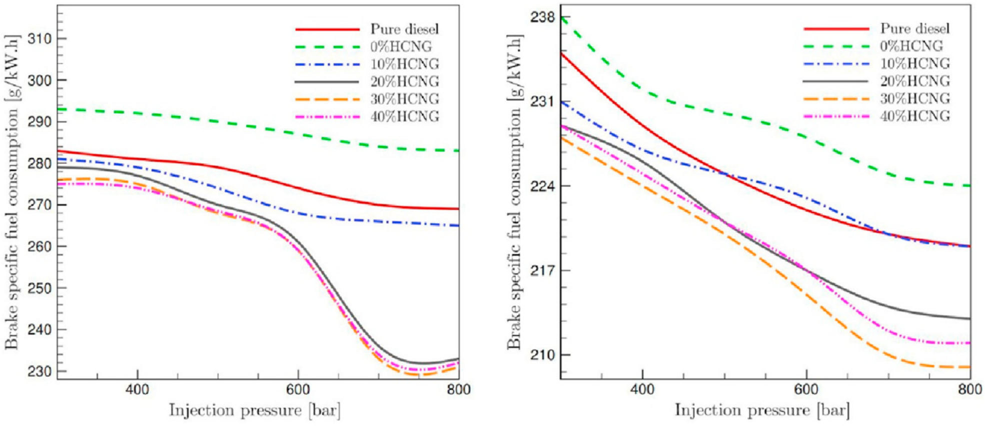
Engine brake thermal efficiency

In this research, the amount of Brake thermal efficiency for HCNG with different contents of hydrogen and also for pure diesel compared to each other in different A/F ratios and injection pressures (with A/F ratio of 40:1) at two constant engine speeds (1200 and 2400 rpm). The results show that in comparison to pure diesel and CNG, brake thermal efficiency improved by increasing hydrogen concentration in the HCNG blend, due to a better homogenous mixture between hydrogen and air (because of hydrogen's higher diffusivity). Based on obtained data, by using HCNG blend with 40% hydrogen in comparison to pure diesel, brake thermal efficiency would be increased up to 14.85% and 8.44% at 1200 and 2400 rpm, respectively (Fig. 7). Also, a higher compression ratio using hydrogen blended fuel is another reason for higher thermal efficiency in comparison to fossil fuels.

Engine specific fuel consumption

In comparison to pure diesel and CNG without hydrogen addition, the amount of brake specific fuel consumption decreases by adding hydrogen to CNG. Fig. 8 shows the amount of brake specific fuel consumption in various engine speeds. Due to hydrogen's higher calorific value, the more hydrogen concentration increases, the less fuel consumption occurs. Using HCNG with 30% of hydrogen instead of pure diesel would reduce specific fuel consumption by up to 38 g/kW.h and 10 g/kW.h at 1200 and 2400 rpm, respectively.

Fig. 9 shows the relation between injection pressure (with A/F ratio of 40:1) and brake specific fuel consumption. As



(a) 1200rpm (b) 2400rpm

Fig. 9 – The amount of specific fuel consumption with various injection pressures.

Please cite this article as: Zareei J et al., The effect of hydrogen addition to compressed natural gas on performance and emissions of a DI diesel engine by a numerical study, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.09.027

shown, in higher injection pressures the amount of brake specific fuel consumption becomes less.

Engine output emissions

In this job, the amounts of HC, Soot, and NO_x emissions of the 3-cylinder turbocharged DI engine were captured. As shown in Fig. 10 the effect of hydrogen addition to CNG has been compared to diesel and CNG in various engine speeds. It indicates the fact that chemical properties of H_2 such as high diffusivity, high ignition temperature, also higher burning velocity, in comparison to other hydrocarbon fuels would decrease the HC and Soot, released from the engine but increases the oxides of nitrogen produced from the combustion process.

Engine HC emission

HC, which produces due to amounts of fuel that cannot be burnt completely, is higher in diesel than HCNG engines. The main reasons are the higher combustion temperature, which results in complete combustion, wider flammability, and higher calorific value of hydrogen. As shown in Fig. 10 when the engine speed increases, the amounts of unburned hydrocarbons become less. The least value among all tested fuels belongs to HCNG with 40% hydrogen content, which averagely decreases HC up to 41.95% in comparison to pure diesel and 8.15% compared to CNG without hydrogen content. In this job also, HC emission calculated at two constant engine speeds (1200 and 2400 rpm) in various injection pressures (with A/F ratio of 40:1) and as the results showed in Fig. 11, indicates that in higher injection pressures the less amount of HC produced.

Engine soot emission

Soot is one of the most effective emissions in air pollution, it also causes serious health issues due to its toxic materials. The amount of Soot in neutral gas fuel and its blends with hydrogen is significantly lower than the pure diesel. In diesel fuel, because of lower self-ignition temperature and high cetane number, the ignition delay is less than HCNG. Hence there would not be enough time for the fuel to form a uniform mixture which results in higher amounts of Soot. HCNG with 40% content of hydrogen is the cleanest fuel which approximately decreases soot up to 73.24% in comparison to pure diesel and 7.09% compared to CNG. The calculation at two constant engine speeds (1200 and 2400 rpm) and various injection pressures (with A/F ratio of 40:1), it can be proved that in higher injection pressure, shows that the amount of Soot released from the engine becomes less in all tested fuels (Fig. 11).

Engine NO_x emission

Oxides of nitrogen may be the most issue for CNG and HCNG fuels in comparison to Diesel. Although CNG fuels enriched by hydrogen reduce many of the carbonyl emissions, as mentioned before, due to rising in the combustion temperature, it increases NO_x emission of the engine. By adding hydrogen to CNG, the amount of NO_x averagely increased up to 16.25% compared to diesel and 9.95% compared to CNG. Fig. 11 shows the relation between injection pressure (with A/F ratio of 40:1) and NO_x, as shown, it can be understood that despite other emissions, injection pressure has a negative relation with NO_x released from the engine and in higher injection pressures, more amount of NO_x produced.

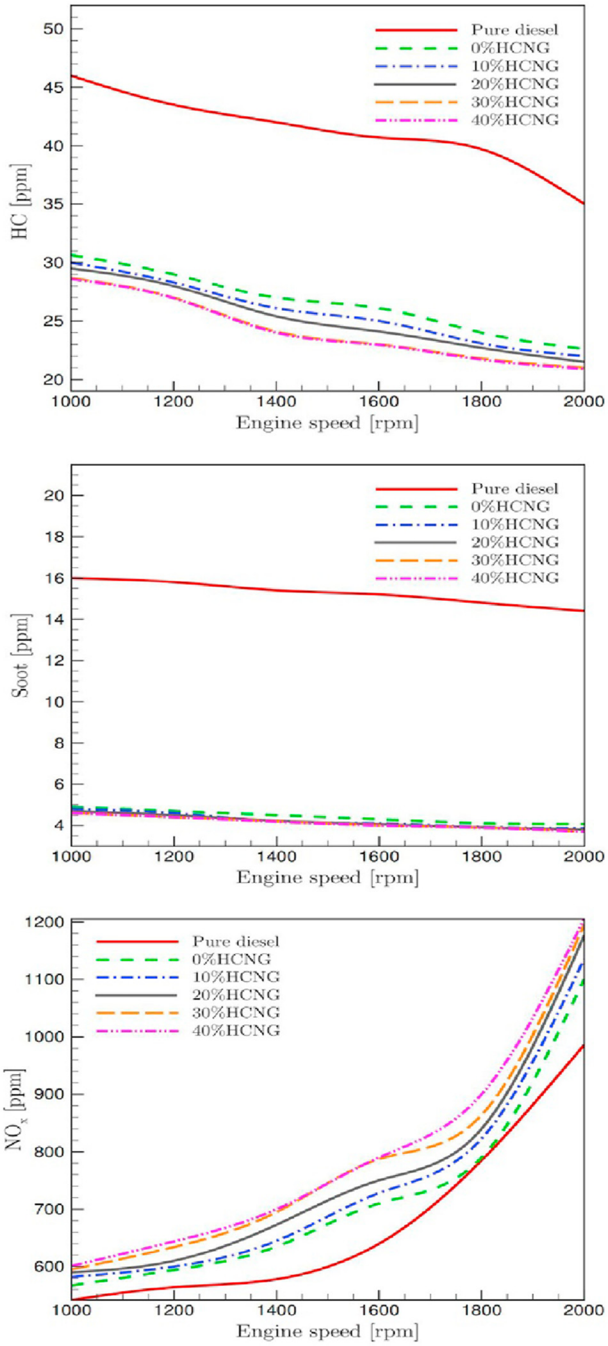
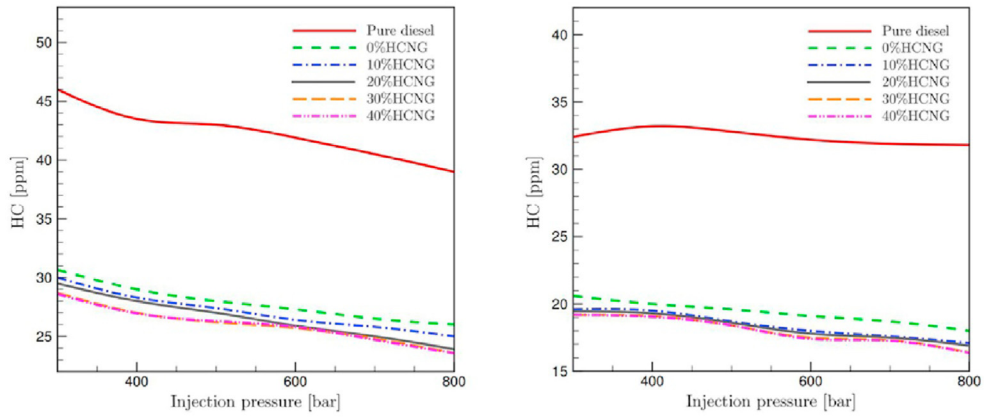
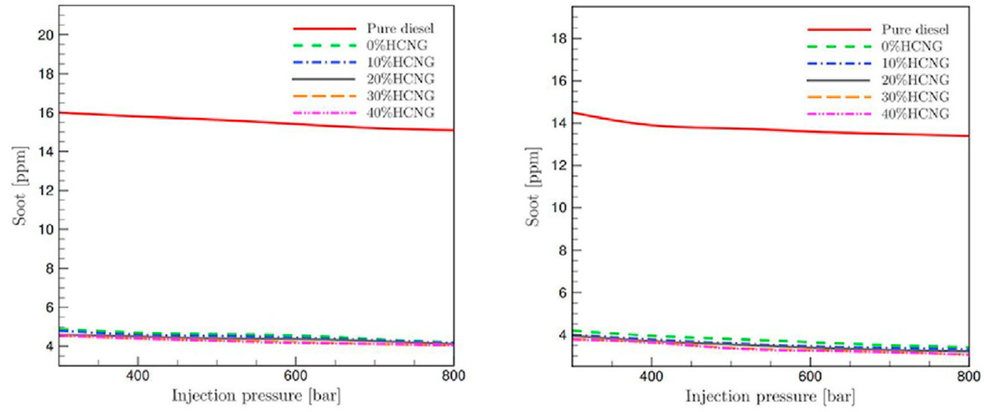


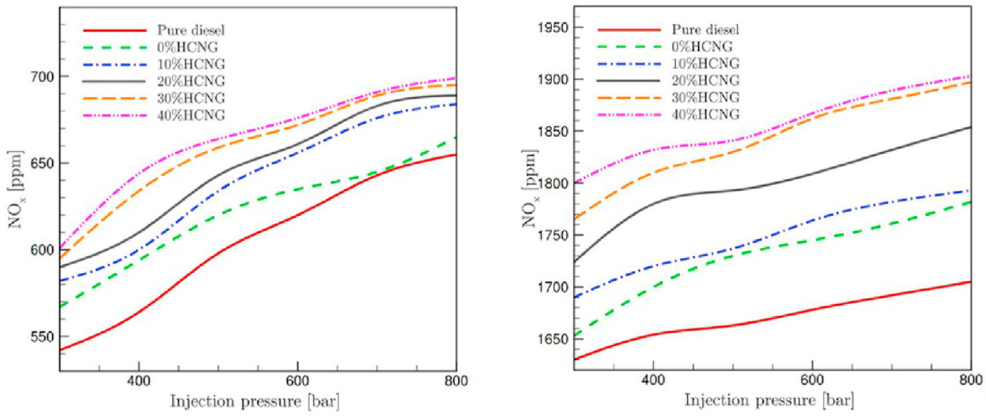
Fig. 10 – The amount of engine HC, Soot, and NO_x emissions in various engine speeds.



(a) 1200rpm (b) 2400rpm



(c) 1200rpm (d) 2400rpm



(e) 1200rpm (f) 2400rpm

Fig. 11 — The amount of engine HC, Soot, and NO_x emissions with various injection pressures.

Conclusions

This study investigates the effect of hydrogen addition to compressed natural gas on the performance and emissions of a DI diesel engine. AVL Fire™ software is used to simulate the engine at different engine Speeds, injection pressure, and Air/Fuel ratios. The main conclusions are listed below.

Results calculated for brake power indicates that at a fuel injection pressure of 800 bar and the Air/Fuel ratio of 40:1, were the optimal values for achieving the highest value of brake power.

40% HCNG was the most suitable fuel for getting the highest brake power among other HCNG blends and pure diesel, which improved brake power 28.07% at 1200 rpm and 21.83 at 2400 rpm.

Please cite this article as: Zareei J et al., The effect of hydrogen addition to compressed natural gas on performance and emissions of a DI diesel engine by a numerical study, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.09.027

Brake thermal efficiency was similar between 40% and 30% of hydrogen in the HCNG blend, and at the Air/Fuel ratio 40:1 with the injection pressure of 800 bar, the maximum brake thermal efficiency occurred which improved by 6.04% at 1200 rpm and 6.73% at 2400 rpm.

Cylinder pressure also was investigated at engine full load condition, and results showed that the optimal Fuel was the Hydrogen-CNG blend with 30% of hydrogen content. Also, this ratio of HCNG can improve the amount of cylinder pressure up to 10% in comparison to pure diesel.

Comparing maximum cylinder pressure between different fuels and different injection pressures with the Air/Fuel ratio of 40:1 at engine full load condition, proves that the highest value for maximum cylinder pressure belongs to 30% HCNG with the injection pressure of 800 bar. And it would be increased up to 7.46% and 11.2% at 1200 and 2400 rpm, respectively.

In comparison to other fuels, the case with 30% hydrogen content and 800 bar injection pressure had the least amount of engine brake specific fuel consumption. Using HCNG with 30% of hydrogen instead of pure diesel would reduce specific fuel consumption by up to 14.13% at 1200 rpm and 4.57% at 2400 rpm.

In this case, the results of the study showed that 40%HCNG has the least amount of HC and Soot. Also, the optimal injection pressure for getting the least HC and Soot emissions achieved the injection pressure of 800 bar.

However using hydrogen-CNG blend improved engine's combustion and efficiency also reduced HC and Soot emissions, it had a negative impact on the amount of NOx released from the engine which can be reduced either by after-treatment equipment, like catalyst converters, or higher rates of EGR.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

[1] An IPCC. Special Report on the impacts of global warming of 1.5 C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In: Intergovernmental panel on climate change; 2018.
[2] Baumeister Christiane, Kilian Lutz. Forty years of oil price fluctuations: why the price of oil may still surprise us. J Econ Perspect 2016;30(1):139–60.
[3] Srinivasan Kalyan K, Krishnan Sundar R, Singh Sabir, Clark Midkiff K, Bell Stuart R, Gong Weidong, Fiveland Scott B, Martin Willi. The advanced injection low pilot ignited natural gas engine: a combustion analysis. 2006. p. 213–8.
[4] BP "BP statistical review of world energy 2019", 68th ed.. London, UK. Available at: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf (Accessed: 23 July, 2020).
[5] Abdullah Shahrir, Wan Mahmood Wan Mohd Faizal, Aljamali Saad, Shamsudeen Azhari. Compressed natural gas direct injection: comparison between homogeneous and stratified combustion. Adv Nat Gas Emerg Technol 2017:153.
[6] Kurniawan Wendy Hardyono, Abdullah Shahrir. Numerical analysis of the combustion process in a four-stroke compressed natural gas engine with direct injection system. J Mech Sci Technol 2008;22(10):1937–44.
[7] Lim Gihun, Lee Sungwon, Park Cheolwoong, Choi Young, Kim Changgi. Effects of compression ratio on performance and emission characteristics of heavy-duty SI engine fuelled with HCNG. Int J Hydrogen Energy 2013;38(11):4831–8.
[8] Ma Fanhua, Naeve Nashay, Wang Mingyue, Jiang Long, Chen Renzhe, Zhao Shuli. Hydrogen-enriched compressed natural gas as a fuel for engines. Nat Gas 2010:307–33.
[9] Mohajan Haradhan. Dangerous effects of methane gas in atmosphere. Int J Econ Polit Integ 2011:3–10.
[10] Hao Duan, Mehra Roopesh Kumar, Luo Sijie, Nie Zhibin, Ren Xiaohui, Ma Fanhua. Experimental study of hydrogen enriched compressed natural gas (HCNG) engine and application of support vector machine (SVM) on prediction of engine performance at specific condition. Int J Hydrogen Energy 2020;45(8):5309–25.
[11] Yan Fuwu, Xu Lei, Wang Yu. Application of hydrogen enriched natural gas in spark ignition IC engines: from fundamental fuel properties to engine performances and emissions. Renew Sustain Energy Rev 2018;82:1457–88.
[12] Faizal M, Chuah LS, Lee C, Hameed A, Lee J, Shankar M. Review of hydrogen fuel for internal combustion engines. J Mech Eng Res Develop 2019;42(3):35–46.
[13] Dhyani Vipin, Subramanian KA. Experimental based comparative exergy analysis of a multi-cylinder spark ignition engine fuelled with different gaseous (CNG, HCNG, and hydrogen) fuels. Int J Hydrogen Energy 2019;44(36):20440–51.
[14] Navarro Emilio, Leo Teresa J, Corral Roberto. CO2 emissions from a spark ignition engine operating on natural gas–hydrogen blends (HCNG). Appl Energy 2013;101:112–20.
[15] Tangöz Selim, Akansu Selahaddin Orhan, Kahraman Nafiz, Malkoç Yusuf. Effects of compression ratio on performance and emissions of a modified diesel engine fueled by HCNG. Int J Hydrogen Energy 2015;40(44):15374–80.
[16] Park Cheolwoong, Kim Changgi, Choi Young. Power output characteristics of hydrogen-natural gas blend fuel engine at different compression ratios. Int J Hydrogen Energy 2012;37(10):8681–7.
[17] Pichayapat Kasidet, Sukchai Sukruedee, Thongsan Sahataya, Pongtornkulpanich Anan. Emission characteristics of using HCNG in the internal combustion engine with minimum pilot diesel injection for greater fuel economy. Int J Hydrogen Energy 2014;39(23):12182–6.
[18] Loganathan M, Velmurugan A, Page Tom, Gunasekaran E James, Tamilarasan P. Combustion analysis of a hydrogen-diesel fuel operated DI diesel engine with exhaust gas recirculation. Front Energy 2017;11(4):568–74.
[19] Kumamoto Ayumi, et al. Measurement of minimum ignition energy in hydrogen-oxygen-nitrogen premixed gas by spark discharge. J Phys Conf 2011;301(1).
[20] Chen Hao, He Jingjing, Zhong Xianglin. Engine combustion and emission fuelled with natural gas: a review. J Energy Inst 2019;92(4):1123–36.
[21] Singh Sauhard, Mishra Sumit, Mathai Reji, Sehgal AK, Suresh R. Comparative study of unregulated emissions on a heavy duty CNG engine using CNG & hydrogen blended CNG as fuels. SAE Int J Eng 2016;9(4):2292–300.

Please cite this article as: Zareei J et al., The effect of hydrogen addition to compressed natural gas on performance and emissions of a DI diesel engine by a numerical study, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.09.027

[22] Nag Sarthak, Sharma Priybrat, Gupta Arpan, Dhar Atul. Combustion, vibration and noise analysis of hydrogen-diesel dual fuelled engine. Fuel 2019;241:488–94.
[23] Koten H. Hydrogen effects on the diesel engine performance and emissions. Int J Hydrogen Energy 2018;43(22):10511–9.
[24] Park Cheolwoong, Kim Changgi, Choi Young, Lee Janghee. Operating strategy for exhaust gas reduction and performance improvement in a heavy-duty hydrogen-natural gas blend engine. Energy 2013;50:262–9.
[25] Xu Jian, Zhang Xin, Liu Jianhua, Fan Longfei. Experimental study of a single-cylinder engine fueled with natural gas–hydrogen mixtures. Int J Hydrogen Energy 2010;35(7):2909–14.
[26] Park Cheolwoong, Lee Sungwon, Lim Gihun, Choi Young, Kim Changgi. Effect of mixer type on cylinder-to-cylinder variation and performance in hydrogen-natural gas blend fuel engine. Int J Hydrogen Energy 2013;38(11):4809–15.
[27] Tarabet L, Lounici MS, Loubar K, Khiari K, Bouguessa R, Tazerout M. Hydrogen supplemented natural gas effect on a DI diesel engine operating under dual fuel mode with a biodiesel pilot fuel. Int J Hydrogen Energy 2018;43(11):5961–71.
[28] Abdelaal Mohsen M, Rabee Basem A, Hegab Abdelrahman H. Effect of adding oxygen to the intake air on a dual-fuel engine performance, emissions, and knock tendency. Energy 2013;61:612–20.
[29] Hora Tadveer Singh, Agarwal Avinash Kumar. Experimental study of the composition of hydrogen enriched compressed natural gas on engine performance, combustion and emission characteristics. Fuel 2015;160:470–8.
[30] Ouchikh S, Lounici MS, Tarabet L, Loubar Khaled, Tazerout M. Effect of natural gas enrichment with hydrogen on combustion characteristics of a dual fuel diesel engine. Int J Hydrogen Energy 2019;44(26):13974–87.
[31] Ghazal Osama H. Performance and combustion characteristic of CI engine fueled with hydrogen enriched diesel. Int J Hydrogen Energy 2013;38(35):15469–76.
[32] Karagöz Yasin, Güler İlker, Sandalcı Tarkan, Yüksek Levent, Dalkılıç Ahmet Selim. Effect of hydrogen enrichment on combustion characteristics, emissions and performance of a diesel engine. Int J Hydrogen Energy 2016;41(1):656–65.
[33] Roy Murari Mohon, Tomita Eiji, Kawahara Nobuyuki, Harada Yuji, Sakane Atsushi. An experimental investigation on engine performance and emissions of a supercharged H2-diesel dual-fuel engine. Int J Hydrogen Energy 2010;35(2):844–53.
[34] Mathur HB, Das LM, Patro TN. Hydrogen-fuelled diesel engine: performance improvement through charge dilution techniques. Int J Hydrogen Energy 1993;18(5):421–31.
[35] Köse H, Ciniviz M. An experimental investigation of effect on diesel engine performance and exhaust emissions of addition at dual fuel mode of hydrogen. Fuel Process Technol 2013;114:26–34.
[36] SinghYadav Vinod, Soni SL, Sharma Dilip. Performance and emission studies of direct injection CI engine in duel fuel mode (hydrogen-diesel) with EGR. Int J Hydrogen Energy 2012;37(4):3807–17.
[37] Deniz Cengiz, Zincir Burak. Environmental and economical assessment of alternative marine fuels. J Clean Prod 2016;113:438–49.
[38] Subramanian M. Performance analysis of 18% HCNG fuel on heavy duty engine. No. 2014-01-1453. SAE Technical Paper. 2014.
[39] Syed Sirajuddin, Renganathan Manimaran. NOx emission control strategies in hydrogen fuelled automobile engines. Aust J Mech Eng 2019:1–23.
[40] Demirci Abdurrahman, Koten Hasan, Metin Gumus. The effects of small amount of hydrogen addition on performance and emissions of a direct injection compression ignition engine. Therm Sci 2018;22(3):1395–404.
[41] Huang Zuohua, Wang Jinhua, Liu Bing, Zeng Ke, Yu Jinrong, Jiang Deming. Combustion characteristics of a direct-injection engine fueled with natural gas–hydrogen blends under different ignition timings. Fuel 2007;86(3):381–7.
[42] Dimopoulos P, Boulouchos Konstantinos, Rechsteiner C, Soltic P, Hotz R. Combustion characteristics of hydrogen-natural gas mixtures in passenger car engines. SAE Trans 2007:1564–76.
[43] Mehra Roopesh Kumar, Duan Hao, Luo Sijie, Rao Anas, Ma Fanhua. Experimental and artificial neural network (ANN) study of hydrogen enriched compressed natural gas (HCNG) engine under various ignition timings and excess air ratios. Appl Energy 2018;228:736–54.
[44] Zareei Javad, Rohani Abbas, Wan Mahmood Wan Mohd Faizal. Simulation of a hydrogen/natural gas engine and modelling of engine operating parameters. Int J Hydrogen Energy 2018;43(25):11639–51.
[45] Rocha Hendrick Maxil Zárate, da Silva Pereira Ricardo, Martins Nogueira Manoel Fernandes, Pereira Belchior Carlos Rodrigues, de Lima Tostes Maria Emilia. Experimental investigation of hydrogen addition in the intake air of compressed ignition engines running on biodiesel blend. Int J Hydrogen Energy 2017;42(7):4530–9.
[46] Kalsi Sunmeet Singh, Subramanian KA. Experimental investigations of effects of hydrogen blended CNG on performance, combustion and emissions characteristics of a biodiesel fueled reactivity controlled compression ignition engine (RCCI). Int J Hydrogen Energy 2017;42(7):4548–60.
[47] Parthasarathy M, Isaac JoshuaRamesh Lalvani J, Dhinesh B, Annamalai K. Effect of hydrogen on ethanol–biodiesel blend on performance and emission characteristics of a direct injection diesel engine. Ecotoxicol Environ Saf 2016;134:433–9.
[48] Deheri Chinmay, Kumar Acharya Saroj, Nath Thatoi Dhirendra, Ambica Prasad Mohanty. A review on performance of biogas and hydrogen on diesel engine in dual fuel mode. Fuel 2020;260:116337.
[49] Zareei Javad, Rohani Abbas. Optimization and study of performance parameters in an engine fueled with hydrogen. Int J Hydrogen Energy 2020;45(1):322–36.
[50] AVL FIRE user manual, version 2014. 2014.
[51] LeVeque R. Finite volume Methods for hyperbolic problems (cambridge texts in applied mathematics). Cambridge: Cambridge University Press; 2002. https://doi.org/10.1017/CBO9780511791253.
[52] Bose Probir Kumar, Maji Dines. An experimental investigation on engine performance and emissions of a single cylinder diesel engine using hydrogen as inducted fuel and diesel as injected fuel with exhaust gas recirculation. Int J Hydrogen Energy 2009;34(11):4847–54.
[53] Eidevåg Tobias, Lindström Martin. Predictions of the flow in the intake port of an engine using LES and PANS. Master's thesis. 2013.
[54] Barbouchi Zouhaier, Bessrour Jamel. Turbulence study in the internal combustion engine. J Eng Technol Res 2009;1(9):194–202.

Please cite this article as: Zareei J et al., The effect of hydrogen addition to compressed natural gas on performance and emissions of a DI diesel engine by a numerical study, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.09.027

[55] Rao Anas, Mehra Roopesh Kumar, Duan Hao, Ma Fanhua. Comparative study of the NOx prediction model of HCNG engine. Int J Hydrogen Energy 2017;42(34):22066–81.

[56] Zeldovich YB, Sadovnikov PY, Frank-Kamenetskii DA. Oxidation of nitrogen in combustion, translation by M Shelef. Moscow-Leningrad: Academy of Sciences of USSR, Institute of Chemical Physics; 1947.

[57] Bogensperger M. A comparative study of different calculation approaches for the numerical simulation of thermal NO formation. 1996. Diss. U. Graz.

[58] Borman GL, Ragland KW. Combustion engineering. New York: McGraw-Hill; 1998.

[59] Zareei J, Rohani A, Mohd W. Combined effect of ignition and injection timing along with hydrogen enrichment to natural gas in a direct injection engine on performance and exhaust emission. Int J Artif Intell Expet Syst 2018;8(1):2614–32.

[60] Izweik Husni Taher. CFD investigations of mixture formation, flow and combustion for multi-fuel rotary engine. 2009.

Please cite this article as: Zareei J et al., The effect of hydrogen addition to compressed natural gas on performance and emissions of a DI diesel engine by a numerical study, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.09.027