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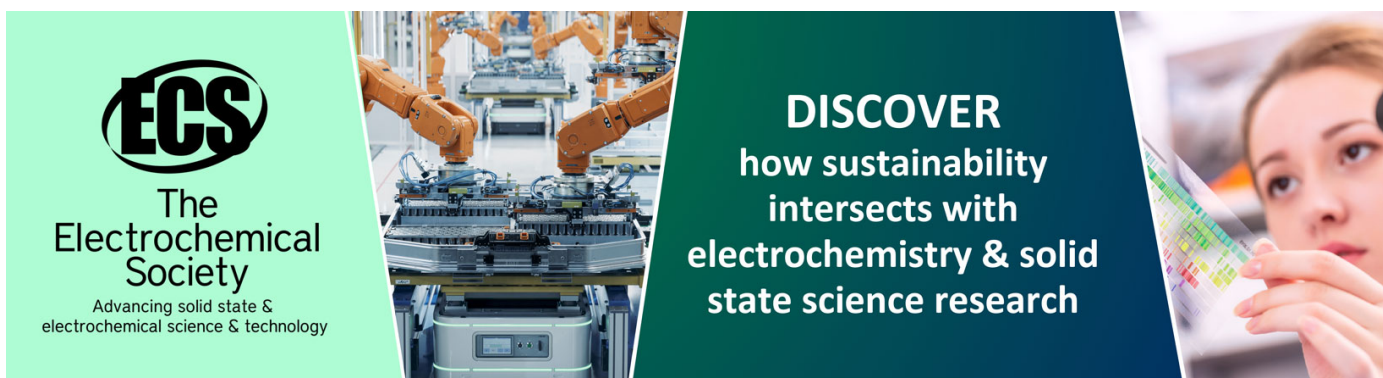
Hydrogen a new fuel for internal combustion engines

To cite this article: D Gheorghe *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **595** 012032

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Hydrogen a new fuel for internal combustion engines

D Gheorghe¹, D Tutunea¹, M Bică¹, A Gruia¹ and M Calbureanu¹

¹ Road Vehicle and Transportation Department, University of Craiova, Craiova, Romania

E-mail: marinbica52@gmail.com

Abstract. The depletion of fossil fuels and the strict emissions regulations have motivated researchers to find and invest considerable resources in finding new renewable fuels. Hydrogen can be used in automotive industry to control the pollutant emissions and to improve engine performances. However, the producing of hydrogen is expensive, the supply infrastructure is not ready and the engines are affected by knocking phenomena and the increase of NO_x emissions. The focus is now in the research of advance combustion technologies such dual fuel engines, homogeneous charge compression ignition (HCCI) and low-temperature combustion (LTC). The main limitations, challenges and perspectives are presented.

1. Introduction

The fuel depletion, environmental pollution and rapid increase in energy demand have pushed researchers to make studies to improve the process of combustion of internal combustion (IC) engines. The stringent regulations to reduce harmful emissions have promoted in the last years the use of low carbon or carbon-neutral alternative fuels combined with new solutions to enhance the charge flow, develop new emission controlling technologies and improve the mixture combustion process [1]. The idea of using hydrogen is not new and researchers around the world have been working to improve the technology in various aspects as production, storage, transport and utilization [2]. Also engine manufacturers have taken the initiative to develop hydrogen operated engines (Zetec 2.0 L from Ford, 6.0 L V12 bi-fuel from BMW). Ganesh et al. [3] investigated in a gasoline engine the effect of hydrogen on emissions and performance and found that the power output was 20% lower than gasoline and the NO_x was four times higher than gasoline with negligible emissions of HC and CO. Park et al. [4] added hydrogen in a natural gas engine at various excess air ratios and found an improve engine combustion with reduce HC, CO and NO_x emissions than the original engine. Saravanan and Nagarajan [5] tested different blends of hydrogen and found that engine brake thermal efficiency increased with 15% after hydrogen addition at 75% load, a dramatically decrease of Smoke, CO and CO₂ with nearly the same NO_x emissions as pure diesel engine. Wang et al. [6–9] studied the hydrogen addition at gasoline engines and found that hydrogen–gasoline blends could reduce HC and CO emissions at cold start and improve engine indicated thermal efficiency. Huang et al. [10–12] conducted experiments on the laminar burning velocities of the hydrogen-enriched fuels and found that the flame speed of hydrogen could reach 15 m/s, which were higher about five times than the speed of methanol. Bose et al. [13] investigated the effect on adding hydrogen in a diesel engine with a compression ratio of 17.5. The hydrogen was supplied constantly at 0.15 kg/h at all loads. The brake thermal efficiency increased with 3.9% comparative with petrodiesel fuel at 80% engine load. Dhyani and Subramanian [14] investigated on a multi-cylinder engine the effect of knock parameters such as injection timing, spark timing and equivalence ratio and found that knock and backfire were related to



each other at higher equivalence ratio. Ceviz et al. [15] conducted experiments on hydrogen addition at a spark-ignition engine. The speed was kept constant at 2000 rpm using hydrogen fractions of 0%, 2.14%, 5.28% and 7.74% by volume as fuel. The hydrogen provided an improvement in the total brake-specific fuel consumption a reduction in HC and CO emissions, an increase in NO_x emissions due to higher flame speed. The scope of this paper is to evaluate the possibility to use hydrogen as an alternative fuel for the internal combustion engine as primary fuel or in dual fuel operation.

Table 1. Main characteristics of hydrogen versus natural gas, gasoline and diesel liquid fuels [16].

		Hydrogen	Natural gas	Gasoline ^(b)	Diesel ^(b)
Density at NTP ^(a)	(kg/m ³)	0.09	0.7-0.9	737	820-950
Energy content	(MJ/kg)	120-142	53.6	46.4	48
Autoignition temperature	(K)	858	813	520-583	473
Flammability limits	(% gas-to-air volume ratio)	4-75	5-15	1.4-7.6	0.6-7.5
Minimum ignition energy	(mJ)	0.02	0.29	-	-
Quenching gap at NTP ^(a)	(mm)	0.64	2.1	-	-
Diffusion coefficient into air at NTP ^(a)	(cm ² /s)	0.61	0.24 ^(c)	-	-

^a Normal temperature and pressure conditions P = 1 bar, T = 293.15 K
^b Liquid fuels.
^c Diffusion coefficient of methane.

2. Hydrogen generation methods

The hydrogen quantity which exists on Earth is small and undeterminable and due to his very low density is pushed out from the gravitational attraction of the planet. It is necessary that hydrogen to be produced from other sources of raw material such as natural gas, oil, coal and water. To produce hydrogen an energy sources is needed as fossil fuels, nuclear or and renewable energy (solar, wind, geothermal and hydroelectric power) [16]. In recent years the majority of the hydrogen produced is from fossil fuels which is costly and produce high emissions. To produce hydrogen by renewable sources and economically is the key to a successful transition to a new hydrogen era. The hydrogen can be produced by several methods such as:

- Natural gas reforming. This method is the cheapest and efficient and is used frequently worldwide. Natural gas is reacted in the presence of synthesis gas and high temperature forming carbon monoxide (CO), a mixture of hydrogen and carbon dioxide (CO₂).
- Gasification. In this method coal, biomass or other materials are burned at high temperature between 1200 and 1500 °C to form gaseous components and then by a series of chemical reactions to hydrogen and carbon monoxide. By this process the hydrogen obtained from biomass is clean with zero greenhouse emission [17].
- Electrolysis. In this process an electric current decompose water in hydrogen and oxygen consuming the highest amounts of energy. It is clean and if the energy is from renewable sources is an emission-free process [18].

3. Hydrogen in CI engines

3.1 Hydrogen only operation

The idea of using hydrogen in compression ignition engines isn't new Homan et al. [19] try to use hydrogen and found that this fuel has high resistance to auto ignition even at compression ratio of 29:1. Later the same authors by using a glow plug ignition reveal that hydrogen ignition delay was short and indicated mean effective pressure is higher that petrodiesel fuel [20]. Naber and Siebers [21] conducted experiments in a constant-volume combustion vessel over a wide range of thermodynamic

conditions and found that ignition delay of hydrogen has a high Arrhenius temperature dependence. Also ignition delay is affected by the temperature. Ikegami et al. [22, 23] used a single cylinder diesel engine to run with hydrogen as only fuel and found that operation range is limited.

3.2 Hydrogen/diesel dual-fuel engines

This solution was proven more realistic to use in compression engines, the hydrogen is combined in various ratio with petrodiesel fuel due to his lower auto ignition temperature. The hydrogen can be injected by carburetor, at the intake ports of the engines or at the intake manifold. Varde and Frame [24] found that the injection of small quantity of hydrogen in the intake of the engine at part load reduce smoke (between 10-15%) and increase oxides of nitrogen. Lilik et al. [25] experiments in a dual fuel engine the injection of hydrogen in the intake air and found an increase in NO_x emissions as is seen in Figure 1. Hydrogen can be mixed with diesel fuel at different rates depending on the speed and the load of the engine, in the literature the researchers use preponderant ratio between 10 and 40%.

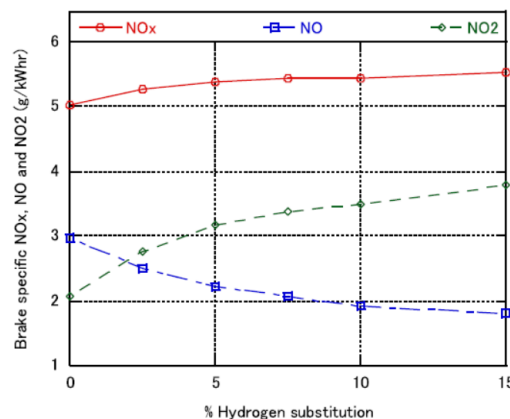


Figure 1. Brake specific NO_x, NO and NO₂ emissions vs. energy percent from hydrogen fuel [25].

Taku and Yasumasa [26] used a single cylinder diesel engine with gas injectors at an intake port and the experiments shows that the engine could achieve higher thermal efficiency than diesel fuel at high engine load conditions. Also the emission of NO_x at higher loads are increased that one of the conventional diesel fuel. In Figure 2 is represented in-cylinder pressure, rate of heat release and diesel fuel injection signal. All rates of heat release have twin peaks, the first peak is due to the combustion of a small amount of diesel fuel and hydrogen and the second is due to the main diesel injection and entrained hydrogen.

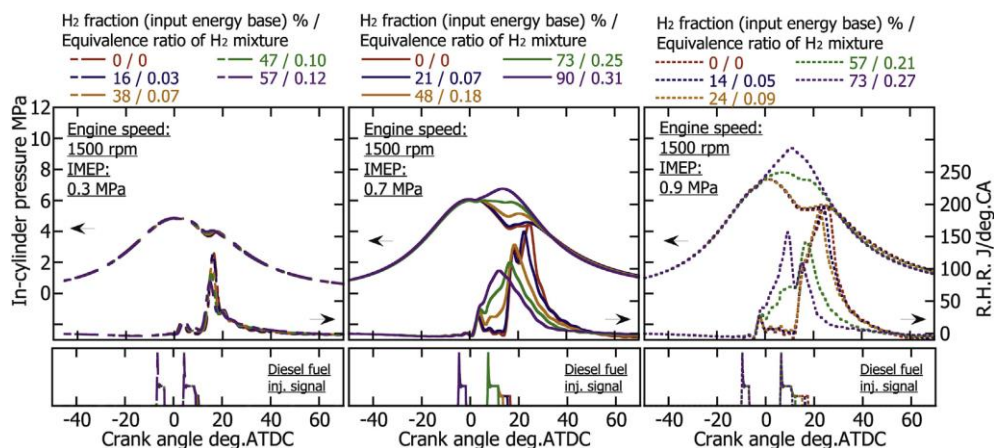


Figure 2. In-cylinder pressure, R.H.R. and diesel fuel injection signal under engine speed of 1500 rpm and IMEP of 0.3, 0.7 and 0.9 MPa condition (parameter: hydrogen fraction) [26].

Karagoz et al. [27] used for experiments a single cylinder, 4 stroke and variable compression ratio. Hydrogen/diesel blend was tested and compare with petrodiesel fuel at 40%, 60%, 75% and 100% engine loads. According to Figure 3, thermal efficiency decreases on each load condition because hydrogen's flame speed is nine times faster than diesel fuel and addition heat flow rises causing the increase of thermal loss. In the Figure 4 is shown the change in pressure due to the high flame speed resulting in fast combustion and increases in peak in cylinder pressure values.

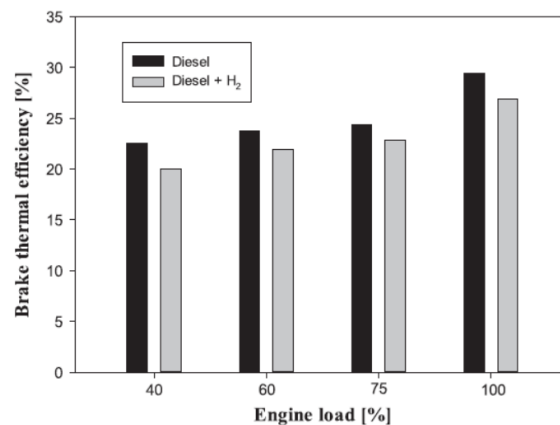


Figure 3. Effect of hydrogen enrichment on thermal efficiency at 40%, 60%, 75% and 100% engine load [27].

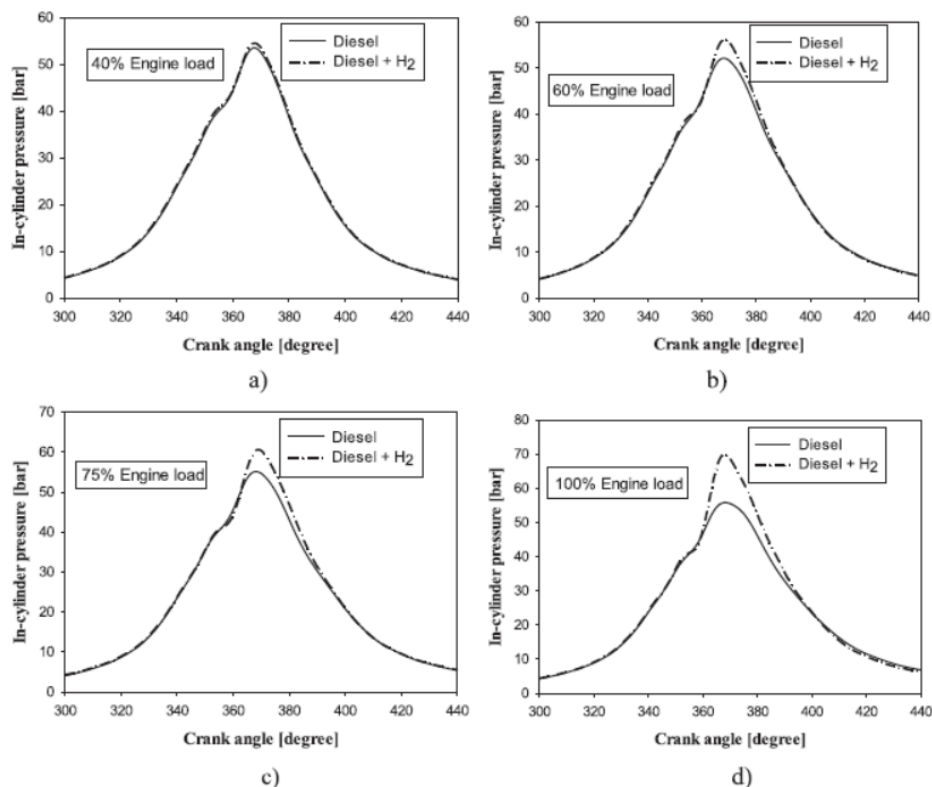


Figure 4. Effect of hydrogen enrichment on in-cylinder gas pressure related to CA at 40%, 60%, 75% and 100% engine loads

The EGR (Exhaust gas recirculation) system was used to reduce NO_x emissions and eliminate knocking of hydrogen-diesel dual fuel engines. Also this solution has many advantages the EGR have

a negative effect on engine efficiency which rise with its percentage. The EGR have a dilution effect increasing smoke, CO and HC emissions due to the lower O₂ levels in the cylinder chambers [28].

3.3 Hydrogen and biofuels

Shirk et al. [29] studied the addition of hydrogen in blends of biodiesel (20%) and petroleum derived diesel fuel (80%) and found that small amounts of hydrogen up to 10% did not affect the steady-state operation of the engine. Kumar et al. [30] used the addition of hydrogen to vegetable oil and found that hydrogen fuel increased the brake thermal efficiency of the engine by 2% and decrease of smoke up to 20% at full load conditions. Also the hydrogen increases the NO_x emissions due to the high combustion rates. Combustion duration was reduced and the ignition delay, maximum rate of pressure and peak pressure increases. Korakianitis et al. [31] conducted experiments on blends of diesel-hydrogen and rapeseed methyl ester-hydrogen and found that rapeseed methyl ester produces similar emission and thermal efficiency trends. Both blends exhibits increase in NO_x emissions, HC, CO and smoke remaining relatively unchanged comparative with normal CI engine operation without hydrogen.

4. Hydrogen in gasoline engines

Ji et al. [32] studied on 1.6 L gasoline engine manufactured by Beijing Hyundai Motors hydrogen and gasoline at various load conditions. The indicated thermal efficiency increases due to the fact that wide flammability and short quenching distance of hydrogen improve combustion especially at idle and lean conditions. Unni et al. [33] investigated on a naturally aspirated single cylinder 396 cc gasoline engines with a carburetor performance and emissions of hydrogen and gasoline. The maximum power obtained with hydrogen (4.8 kW@ 3600 rpm) is lower than gasoline (6.16 kW@ 3600 rpm) and the brake thermal efficiency (BTE) of hydrogen is higher than that of gasoline due to the higher flame speed and very high rate of burning resulting in higher efficiency (Figure 5).

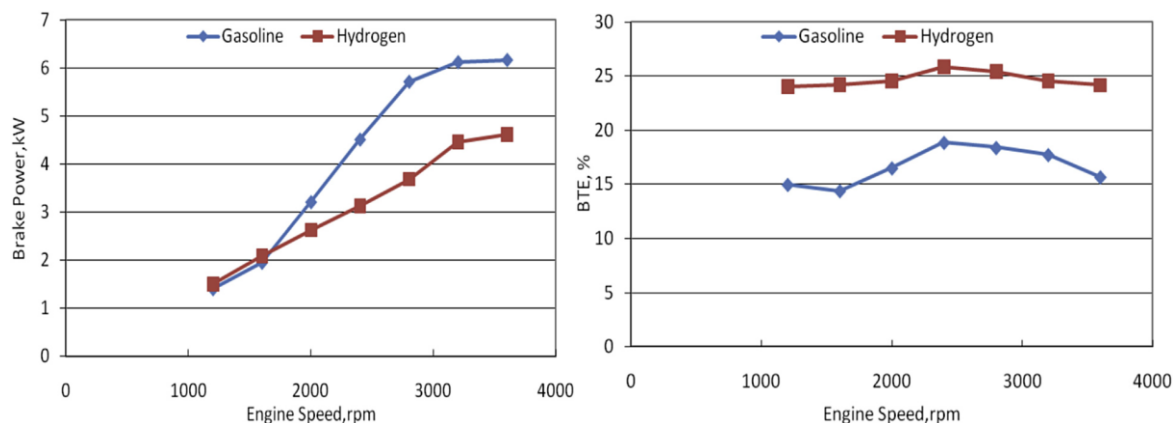


Figure 5. Variation of brake power (left) and brake thermal efficiency (right) with speed [33].

Sun et al. [34] investigated the effects of hydrogen direct injection on performance and engine stability. For the experiments used a four-cylinder SIDI engine with the injector situated between the intake valves and a centrally mounted spark plug. In Figure 6 is presented brake thermal efficiency with ignition timing under different excess air ratios for gasoline and a mixture of 10% hydrogen. Hydrogen addition increases BTE from 6% to 13% in four figures due to the complete combustion of hydrogen shorten combustion duration. Naruke et al. [35] investigated hydrogen addition on a single-cylinder 4-stroke SI engine. Hydrogen was supplied in the middle of the intake line and mixed with air using a static mixer. The value of λ was set to 1.80, 1.84, 1.89, 2.04, and 2.28, which are the lean limits for hydrogen concentrations of 0%, 2%, 4%, 10%, and 20%, respectively. In Figure 7 is presented the indicated thermal efficiency and knock at $\lambda=1.8$. The indicated thermal efficiency at the knock limit was increased by 0.3 point% at a fraction of hydrogen of 4%.

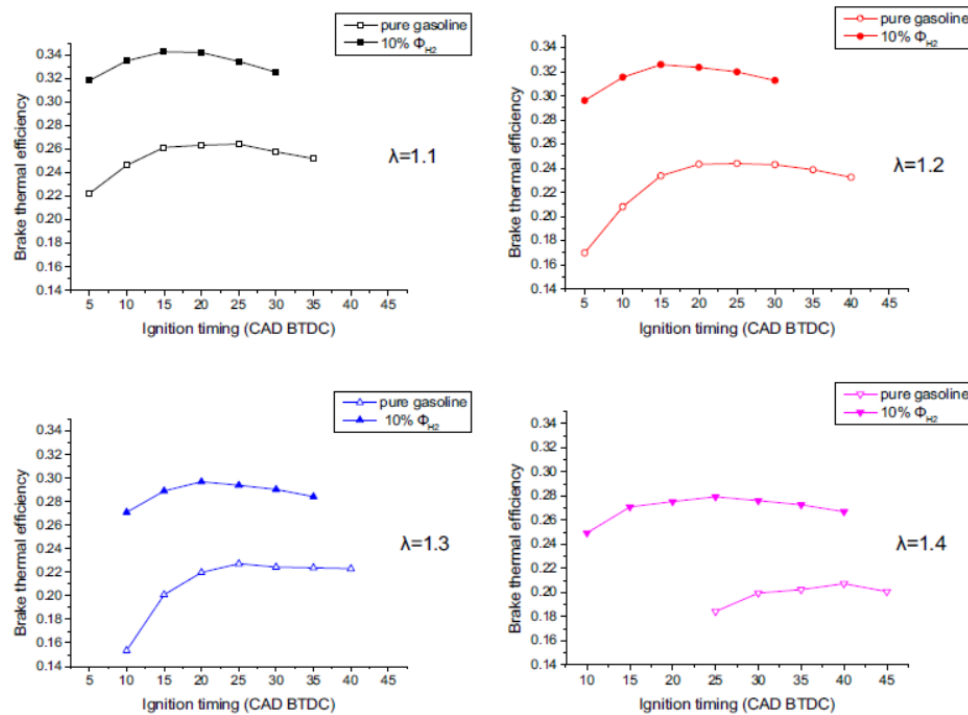


Figure 6. Brake thermal efficiency with ignition timing under different excess air ratios [34].

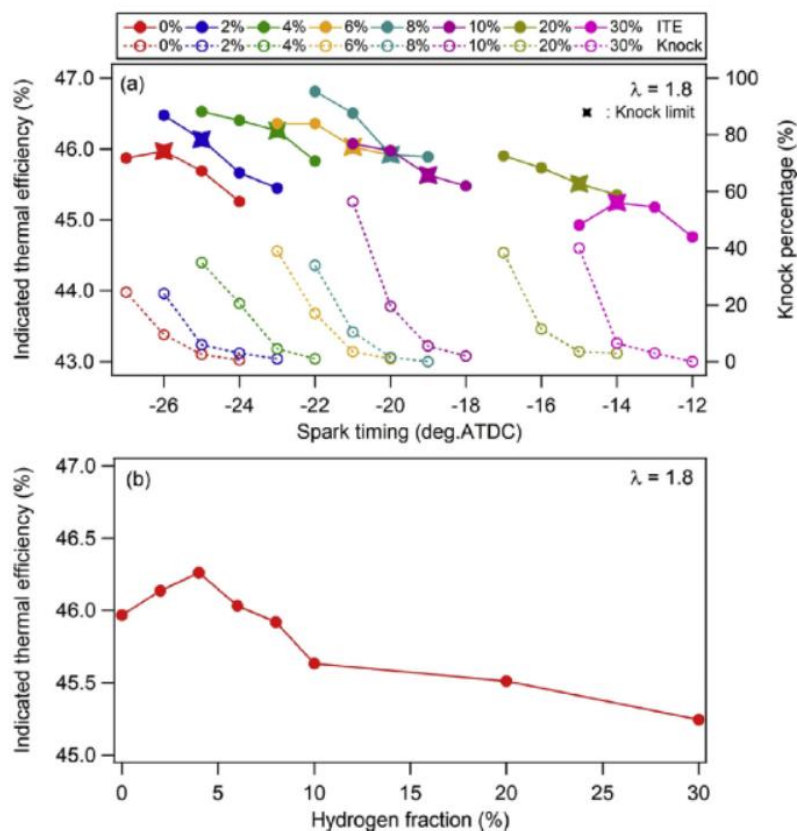


Figure 7. (a) Indicated thermal efficiency and knock percentage at $\lambda=1.8$ and (b) indicated thermal efficiency at knock limits against the hydrogen fraction in heating value at $\lambda=1.8$. Stars in graph (a) show the indicated thermal efficiency at the knock limit under each hydrogen fraction condition [35].

5. Conclusion

The future of diesel engine especial due the dieselgate scandal is considered ambiguous by many researchers and new actions are needed to advance the combustion performance and emissions production of the engine. The implementation of alternative fuels such as hydrogen with a carbonless structure with high energy content can be a solution. Hydrogen addition in internal combustion engines provide a decrease in HC, CO, CO₂ and smoke levels and an increase in heat release rate and brake thermal efficiency. However, the rise of the temperature in the combustion chamber brings an undesirable phenomenon the rise of NO_x particularly at high load conditions. Applying EGR system can reduce the NO_x formation but this system increases the smoke, CO and HC emissions do to the decrease of O₂ levels in the cylinder chambers. Depending on the type of engine used (burning of oil) and the air-fuel ratio (operating strategy used rich versus lean), a hydrogen fuelled engine can produce high NO_x and significant carbon monoxide emissions to almost zero emissions. Hydrogen has high energy content by weight, but not by volume which is a challenge for storage and long term use.

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