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A REVIEW of HYDROGEN-ENRICHED COMPRESSED NATURAL GAS (HCNG)-FUEL in DIESEL ENGINES

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Abstract

In recent years, due to reduction of finite petroleum resources, and both environmental pollution criteria, researchers give to particularly a distinct importance on the usage of alternative fuels in internal combustion engines (ICEs). The one way of to regulate these environmental pollution is reducing the emissions. Resulting from this requirement, many scientists have suggested various solutions for diesel engines, one of which is the use of gaseous fuels as a supplement for liquid diesel fuel. The most important objectives of these "dual-fuel" diesel engines are to provide high efficiency and clean combustion. Therefore, hydrogen-enriched compressed natural gas (HCNG) plays an important role for a promising alternative fuel types for diesel engines. This review article is given of contemporary research and offers a comprehensive overview on the HCNG fueled diesel engines. Main topics that are discussed include introduction and fundamentals of the combustion of hydrogen and compressed natural gas blends, history of the Hythane®, details on the different mixture formation strategies and fuel properties, analyze their engine performance and their emissions characteristics, look through the benefits and challenges of HCNG for diesel engines and availability for a state of the art on increasing power output and efficiency while controlling emissions and not modified modeling.

Keywords: *Hydrogen, natural gas, HCNG, diesel engines, pilot injection, fuel consumption, emissions*

1. INTRODUCTION

The difficulty of controlling prices and the uncertain reserves are strong incentives for pursuing energy security. Global warming and local pollution hot spots associated with fossil fuel usage are further significant environmental and societal problems [1]. Natural gas and hydrogen blends can be a viable alternative to pure fossil fuels because of the expected reduction of the total pollutant emissions. These blends offer a valid opportunity for dealing with a sustainable development in transportation sector, in view of the future more stringent emission limits for road vehicles in European Countries [2]. HCNG (hydrogen-enriched natural gas) as a new engine fuel not only owns the advantages of hydrogen and CNG but also overcomes their disadvantages. Using HCNG fuel can improve the fuel economy, decrease CO (Carbon Monoxide), HC (Hydrocarbon) and CO2 (Carbon Dioxide) emissions and realize lean burn [3]. The gaseous fuels are getting more positive response from researchers and end-users compared to past because of current unfolding developments. Therefore, it is more economical and of environmental advantage to use gaseous fuel in diesel engines that use the 'dual-fuel concept' [4]. Most researches have focused on the use of natural gas as an alternative fuel, mainly due to its wide availability, clean burning and low cost compared to other gaseous fuels. In spite of the advantages of natural gas, it has some disadvantages such as low burning velocity and poor lean burn capability. These problems lead to engines having high cyclic variation, longer combustion duration and lower power output. Hydrogen is the best additive candidate to natural gas due to its unique characteristics. Moreover, hydrogen has a wide flammability range which allows higher efficiency with leaner operation for reduced toxic emissions, low ignition delay, and higher flame stability. The effect of adding hydrogen to natural gas can lead to shorter burning time, extended flammability and leaner limits of the mixture. Moreover, hydrogen addition could broaden the range of EGR while maintaining low cyclic variations and low level of NOx emissions [5]. Hythane is a patented mixture of hydrogen and CNG, created by Hydrogen Components, Inc. in Littleton, Colorado. According to US Patient #5,139,002 (Lynch & Marmaro, 1992), Hythane® was invented by Frank Lynch and Roger Marmaro and was granted a US patient in 1992. In this patient, Hythane is defined a blend of hydrogen and natural gas provided for burning in an engine without the need for modifications to engine parameters, and is defined as roughly a 15% blend of Hydrogen in CNG fuel [6] and several demonstrations have been carried out in North America, often with limited commercial operation, (Denver, 1992, Montreal, 1995-1996, Thousand Palms, 1999 and on, Las Vegas, Phoenix, …) and more lately in Europe (Sweden, Italy) and Asia (India and China) [7]. When used in an internal combustion engine, even the addition of small amount of hydrogen to natural gas (5-30% by volume) leads to many advantages, because of some particular physical and chemical properties. According to Dalton's partial pressure law, hydrogen fraction was decided by the partial pressure of these two fuels in HCNG tank. The influence of gas composition on engine behaviour can be adequately characterized by Wobbe index. If the Wobbe index remains constant, change in the gas composition will not lead to a noticeable change in the air-fuel ratio and combustion rate[8].

2. ENGINEERING PROPERTIES OF HCNG:

As we mentioned HCNG is a newly dual-fuel which contains of natural gas and hydrogen components using in the ICEs. Table 1 illustrates the properties of methane and hydrogen [9]. The mole fractions of OH (Hydroxyl) and O increase with hydrogen fraction, while the increase of OH and O improves the rate of combustion and reduces the emissions of HC and CO. This explains that hydrogen addition is good for CNG combustion in molecular scale [3].

Table 1 – Properties of methane and hydrogen.

property	Unit	Methane	Hydrogen
Molar mass	kg/kmol	16.043	2.016
Density (at 1 bar, 25 °C)	kg/m^3	0.648	0.081
Stoichiometric air requirement	kg_{air}/kg_{fuel}	17.2	34.3
	Vol%	9.5	29.5
Lower gravimetric energy density (calorific value)	MJ/kg	50	120
Lower volumetric energy density (350 bar, 25 °C)	MJ/dm^3	11.6	2.8
Mixture calorific value (in air at 1 bar, 25 °C, $\lambda = 1$) external mixture formation	MJ/m^3	3.40	3.19
Mixture calorific value (in air at 1 bar, 25 °C, $\lambda = 1$) internal mixture formation	MJ/m^3	3.76	4.52
Ignition limit (in air at 1 bar, 25 °C)	Vol%	4.4 ÷ 15	4 ÷ 76
	λ–Bereich	2 ÷ 0.6	10 ÷ 0.13
Auto-ignition temperature (in air at 1 bar)	°C	595	585
Laminar flame speed (in air at 1 bar, 25 °C, $\lambda = 1$)	cm/s	≈42	≈230

The laminar burning speed of hydrogen is nearly eight times higher than that of natural gas, so the addition of hydrogen can increase the burning velocity of the mixture, and it brings some advantages such as shorter combustion duration, greater degree of constant volume combustion and improved indicated thermal efficiency [8] and it is also noted that the quench distance of hydrogen is much smaller than that of natural gas, the heat loss to chamber wall will be increased by addition of hydrogen into the natural gas [10]. With other words, enriching natural gas with hydrogen for use in an internal combustion engine is an effective method to improve the burn velocity, with a laminar burning velocity of 2.9 m/s for hydrogen verses a laminar burning velocity of 0.38 m/s for methane [6]. Dual-fuel engines or 'gas diesel engines', usually have the gaseous fuel mixed with the air in the engine cylinders, either through direct mixing in the intake manifold with air or through injection directly into the cylinder. The resulting mixture after compression is then ignited through the injection of a small amount of diesel fuel (the pilot) in the usual way. This pilot liquid fuel auto-ignites to provide ignition sources for subsequent flame propagation within the surrounding gaseous fuel mixture [4]. Additionally [11] reported that, mixing hydrogen into natural gas for direct injection engine combustion is advantageous from the second-law perspective. With increasing hydrogen content, the irreversibility produced during combustion decreases as a percentage of total injected fuel availability, and the second-law efficiency increases. A general chemical HCNG Equilibrium (Eq.1)[12], the combustion of 1 mol of fuel composed of η moles of CH_4 and (1-η) moles of H_2. Assuming complete combustion of the fuel in air with a given air-to-fuel ratio (λ):

$$\eta CH_4+(1-\eta)H_2+\frac{\lambda}{2}(1+3\eta)(O_2+\frac{79}{21}N_2) \rightarrow \eta CO_2+(1+\eta)H_2O+\frac{\lambda-1}{2}(1+3\eta)O_2+\frac{\lambda}{2}(1+3\eta)\frac{79}{21}N_2 . \quad (1)$$

3. EFFECTS OF HCNG ON DIESEL ENGINE PERFORMANCE

The natural gas–hydrogen blends maintained high thermal efficiency at high engine load and the effective thermal efficiency is almost constant or slightly increases with the increase of hydrogen fraction at the small and medium engine loads; Two factors due to hydrogen addition influence the variation of thermal efficiency; on one hand, the increase of combustion velocity by hydrogen addition shortens the combustion duration and increases the thermal efficiency, and on the other hand, the heat loss to the chamber wall will be increased by hydrogen addition due to the decreased quench distance and increased combustion temperature, and this will decrease the thermal efficiency. Brake effective thermal efficiency increased with the increase of hydrogen fraction at low and medium engine loads and high thermal efficiency is maintained at high engine load, which makes it an ideal fuel for high load applications and heavy-duty vehicles [6,10]. One an important detailed about CNG vs HCNG is reported by [8] that, the brake thermal efficiency for HCNG is greater than CNG for the same excess air ratio (λ) and the difference in brake thermal efficiency between HCNG and CNG increases with increasing excess air ratio. Also experimental results indicated that under certain conditions, the maximum cylinder gas pressure, maximum heat release rate increased with the increase of hydrogen fraction. The beginning of heat release advanced with the increase of hydrogen fraction [8]. Another advantage to lean burn is that as the excess air ratio is increased, the brake specific fuel consumption decreases. This is because as the air-fuel ratio is increased, it usually leaves less unburned fuel. That is true until the excess air ratio reaches a certain limit when the cycle-by-cycle variations begin to increase because of the lack of fuel. Lean operation also reduces the likelihood of knocking, which allows the use of a higher compression ratio. The addition of hydrogen can greatly improve the performance and emissions of the fuel. There have been many studies completed in efforts to obtain the ideal hydrogen ratio, and the general consensus is that hydrogen/natural gas blends around 20%, results in the best overall combination of emissions and engine performance [6].Fundamentally, the addition of hydrogen provides a large pool of H and OH radicals whose increase makes the combustion reaction much easier and faster, thus leading to shorter burn duration. With these important engine performance criterions, the pilot injection phenomena and combustion chamber issue should not be forgotten. The optimized design of the combustion chamber is an important way of improving the mechanism of HCNG combustion [2]. The engine operating and design parameters include load, speed, compression ratio, pilot fuel injection timing, pilot fuel mass inducted, intake manifold conditions, and type of gaseous fuel. The amount of pilot fuel needed for this ignition is between 10% and 20% of the operation on diesel alone at normal working loads and the amount differs with the point of engine operation and its design parameters. For a dual-fuel engine or gas diesel engines, diesel combustion phases occurs five parts; the pilot ignition delay , pilot premixed combustion , primary fuel ignition delay, rapid combustion of primary fuel, and the diffusion combustion stage. Summarily, increasing the load at constant speed results in an increase in the mass of gaseous fuel admitted to the engine, since the pilot mass injected remains constant at all loads. This increase in the mass of methane then causes an increase in the ignition delay period of pilot diesel which then auto-ignites and starts burning the gaseous fuel at a higher rate of pressure rise [4].

4. EFFECTS OF HCNG ON DIESEL ENGINE EMISSIONS

When it comes to alternative fuels, arguably the most important factor in determining the feasibility of the fuel is the exhaust emissions. Because of the strictly controlled emissions regulations, it is not only necessary to find a fuel that has optimum performance, but it is also very important to find a fuel that can meet the respective emissions standards. Considering emissions, when HCNG fuel is compared with gasoline and diesel it appears to be a very appealing alternative fuel. When compared with diesel, it nearly eliminates the particulate matter which is often of great concern. Methane has a relatively stable chemical structure, therefore making it difficult to reduce emissions by after treatment. For this reason, the engine fueled with HCNG has a large advantage regarding the hydrocarbon emissions than that of CNG fueling. Probably the largest advantage to running the engine on lean burn is that it has the ability to greatly reduce the NOx emissions. The reduction in NOx emissions are due to the increased airflow which causes the engine to run at a lower temperature, therefore reducing the NOx emissions. Emissions can also be improved with the addition of hydrogen. Compared to pure natural gas, HCNG reduces the HC emissions, which is in part due to the increased combustion stability that comes with the addition of hydrogen. However, due to the increased temperature and combustion duration that accompanies the hydrogen addition, an increase in NOx emissions is observed [6]. A report which has an experimental investigation and reinforced with Figure1, Figure 2 an Figure 3; mentioned that, when excess air ratio changed from 1.2 to 2.0, NOx emission could research to an extremely low level. When excess air ratio was about 1.8, maximum cylinder pressure and maximum heat release have got more significance rise due to hydrogen addition compared to excess air ratio was 1.2. It has been suggested that, when adding more than 20% volume into CNG, lean mixture combustion and ignition timing optimization could significantly decrease NOx emission and maintain relatively higher thermal efficiency under certain fixed engine conditions[8]. Figure 1 and 2 shows the gas consumption and green house gases emissions for different contents of hydrogen in HCGN and local emissions of different volumes of hydrogen in HCNG, respectively. Figure 3 illustrated that emission potential of HCNG engine [8].

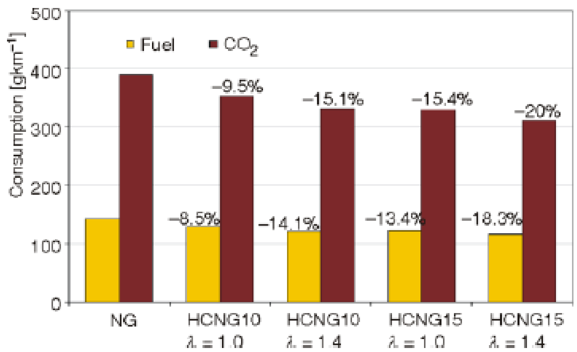

Figure 1. Gas consumption and green house gases emissions for different contents of hydrogen in HCGN

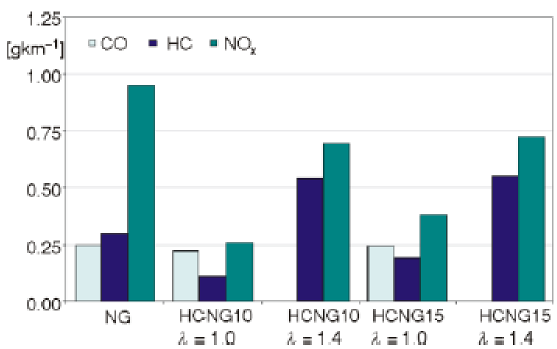

Figure 2. Local emissions of different volumes of hydrogen in HCNG

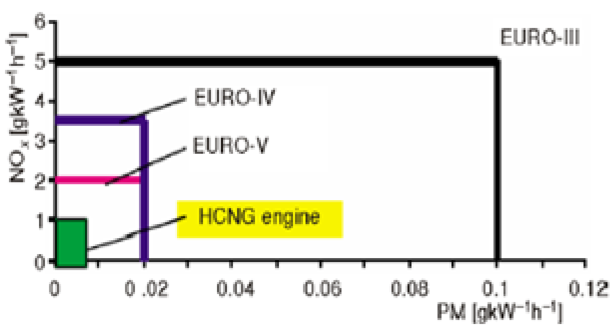

Figure 3. Emission potential of HCNG engine

5. CHALLENGES OF HCNG

One of the biggest challenges using HCNG as a fuel for engines is determining the most suitable hydrogen/natural gas ratio. There is a minor reduction in power output and higher BSFC for the engines at high engine loads and it is important to take prevention on HCNG storage and supply infrastructure. [4, 7, 8]

6. CONCLUSIONS

Researchers in various countries have carried out many experimental and numerical studies using gaseous fuels as diesel engine fuel substitute in a dual-fuel mode of operation. An attempt has been made here to review the previous studies on dual-fuel concept minimizing with hydrogen-enriched natural gas, known as HCNG or Hythane. The overall observation from these experimental results is that the engine operating and design parameters and type of gaseous fuel play an important role in the performance of HCNG engines. Addition of hydrogen and natural gas blends effects of engine performance and emissions were mentioned with detailed. Engineering fundamentals and properties of HCNG were examined and discuss in the review. Lastly look through the challenges of HCNG fuel which use in diesel engines. Especially research on hydrogen and natural gas blends (in more particular HCNG) combustion in the IC engine has intensified, the number of published papers in the field of hydrogen and natural gas –diesel combustion is not as rich as for the hydrogen and/or natural gas used in spark ignited engines. According to this situation, authors survey the limited previous works and curve out the review of HCNG in CI engines.

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