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Performance Review of Hydrogen in Internal Combustion Engine

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Abstract- The fast depletion of fossil fuels is urgently demanding a carry out work for research to find out viable alternative fuels for meeting sustainable energy demand with minimum environment impact. In the future, our energy systems will need to be sustainable and renewable, and cost- effective and efficient, convenient and safe. Hydrogen is expected to be one of the most important fuels in the near future to control emission norms. The use of the hydrogen as a fuel in the internal combustion engine represents an alternative use to replace the hydrocarbons fuels, which produce polluting gases such as hydro carbon (HC), carbon monoxide (CO) during combustion. This review work is on the hydrogen-fueled internal combustion Engine. The first hydrogen-engine fundamentals were described by examining the engine-specific properties of hydrogen and then existing literature were surveyed.

Keywords- hydrogen, emissions, alternative fuel, internal combustion engine, power

I. INTRODUCTION

The hydrocarbon fuels have played a leading role in propulsion and in the field of power generation. However, increase in stringent environment regulations on exhaust emissions and anticipation of the future depletion of worldwide petroleum reserves provides strong encouragement for research on alternative fuels [1]. As a result various alternative fuels (such as compressed natural gas (CNG), liquefied petroleum gas (LPG), bio gas, hydrogen, vegetable oils, producer gas) have been considered as substitutes for hydrocarbon-based fuel and reducing exhaust emissions. Of these, hydrogen is a long-term renewable and less-polluting fuel. In addition hydrogen is clean burning characteristics and better performance drives more interest in hydrogen fuel. When it is burnt in an internal combustion engine, the primary combustion product is water with no CO_2. NO_x emission formed when hydrogen is used [2, 7]. There are various distinct feature of hydrogen that greatly influences the technological development of hydrogen internal combustion engine.

Compared to nearly all other fuels, hydrogen has a wide flammability range (5-75% versus 1.5-7.8 % volume in air for gasoline). This is closely related over the safe handling of hydrogen. Also it shows wide range of air-fuel mixtures, including a lean mixture of air to fuel, or, in other words, a fuel-air mix in which the amount of fuel is less than the stoichiometric, or chemically ideal, amount. Running an engine on a lean mix generally allows for greater fuel economy due to a more complete combustion of the fuel. In addition, it also allows for a lower combustion temperature, lowering emissions of criteria pollutants such as nitrous oxides (NO_x) [3].

Hydrogen has a small quenching distance (0.6 mm for hydrogen versus 2.0 mm for gasoline), which refers to the distance from the internal cylinder wall where the combustion flame extinguishes. This implies that it is more difficult to quench a hydrogen flame than the flame of most other fuels, which can increase backfire since the flame from a hydrogen-air mixture more readily passes a nearly closed intake valve, than a hydrocarbon-air flame [3, 17].

Hydrogen burns with a high flame speed, allowing for hydrogen engines to more closely approach the thermodynamically ideal engine cycle (most efficient fuel power ratio) when the stoichiometric fuel mix is used. However, when the engine is running lean to improve fuel economy, flame speed slows significantly [3].

Flame velocity and adiabatic flame temperature are important properties for satisfactory performance of an engine, and to obtain good thermal efficiency, stability of flame propagation and the exhaust flue gases with uniform velocity and temperature of the flame. The equivalence ratio as a function of flame velocity and temperature is shown in fig. 1 and 2 respectively.

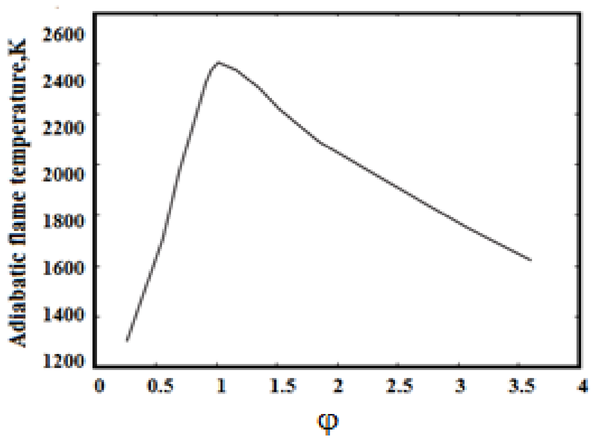

Fig.1. Adiabatic flame temperature [5]

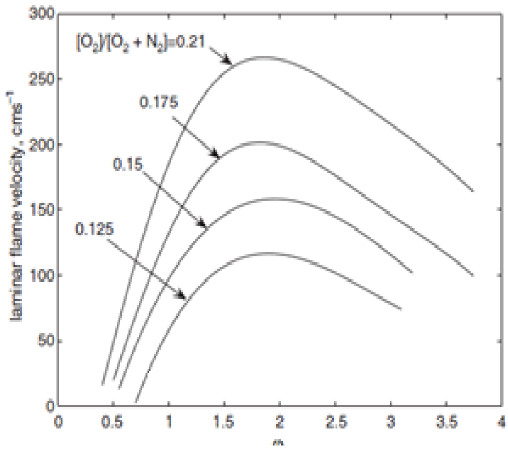

Fig.2 laminar flame velocity for hydrogen, Nitrogen mixtures, gasoline and air mixtures [5]

II. HYDROGEN AS A FUEL

Hydrogen produces only water after combustion. It is a non-toxic, non-odorant gaseous matter and also can be burn completely [7]. When hydrogen is burned, hydrogen combustion does not produce toxic products such as hydrocarbons, carbon monoxide, and oxide of sulfur, organic acids or carbon dioxides shown in Eq. (1), except for the formation of NOx [8].

$$2H_2O+ O_2 = 2H_2O\ldots \ (1)$$

Due to these outcomes it is feasible to use hydrogen as an alternative fuel in internal combustion engines. The comparisons of hydrogen with other fuels are given in Table 1. Combustion of hydrogen is fundamentally different from the combustion of hydrocarbon fuel [9].

Table1. Comparison of hydrogen with other fuels [26]

Fuel	LHV (MJ/kg)	HHV (MJ/kg)	Stoichiometric Air/Fuel Ratio (kg)	Combustible Range (%)	Flame Temp(°C)	Min. Ignition Energy (MJ)	Auto Ignition Temp. (°C)
Methane	50.0	55.5	17.2	5-15	1914	0.30	540-630
Propane	45.6	50.3	15.6	2.1-9.5	1925	0.30	450
Octane	47.9	15.1	0.31	0.95-6	1980	0.26	415
Methanol	18.0	22.7	6.5	6.7-36	1870	0.14	460
Hydrogen	119.9	141.6	34.3	4-75	2207	0.017	585
Gasoline	44.5	47.3	14.6	1.3-7.1	2307	0.29	260-460
Diesel	42.5	44.8	14.5	0.6-5.5	2327	-	180-320

2.1 Performance in Diesel Engine

There are several reasons for applying hydrogen as an additional fuel to accompany diesel fuel in the internal combustion (IC) compression ignition (CI) engine. Firstly, it increases the H/C ratio of the fuel injected by inducting lean amounts of hydrogen to a diesel engine could decrease heterogeneity of a diesel fuel spray due to the high diffusivity of hydrogen which makes the combustible mixture better premixed with air and more uniform [13]. Hence the formation of hydrocarbon, carbon monoxide, and carbon dioxide during the combustion can be completely avoided; however a trace amount of these compounds may be formed due to the partial burning of lubricating oil in the combustion chamber [14]. However hydrogen cannot be used as a sole fuel in a compression ignition (CI) engine, since the compression temperature is not enough to initiate the combustion due to its higher self-ignition temperature [25].Hence hydrogen cannot CI engine without the assistance of a spark plug or glow plug. This makes hydrogen unsuitable for a diesel engine. Therefore the activities on hydrogen fuelling of a diesel engine were based on dual-fuel mode. In a dual fuel engine the main fuel is inducted/carbureted or injected into the intake air while combustion is initiated by diesel fuel that acts as an ignition source. The quantity of pilot fuel may be in the range of 10–30% while the rest of the energy is supplied by the main fuel. Hydrogen operated dual fuel engine has the characteristics to operate at leaner equivalence ratios at part loads, which results in NOx reduction, and increase in thermal efficiency thereby reducing the fuel consumption.

It conclude that the diesel engines can be converted to operate on hydrogen–diesel dual mode with up to about 38% of full-load energy substitution without any sacrifice on the performance parameters such as power and efficiency [16].

2.2 Performance in Spark Ignition (SI) Engine

Hydrogen can be used as a fuel directly in an internal combustion engine, almost similar to a spark-ignited (SI) gasoline engine. Most of the past research on H_2 as a fuel focused on its application in spark ignition engines. Hydrogen is one of the best candidate for use in SI engines as a fuel having some unique and most desirable properties like low ignition energy with very

fast flame propagation speed also wide range of operation speed. When hydrogen mixed with air produces a combustible mixture which can be burned in a conventional spark ignition engine at an equivalence ratio below the lean flammability limit of an air fuel mixture. The resulting combustion produces low flame temperatures and leads directly to lower heat transfer cylinder walls, high engine efficiency and lower exhaust of NOx emission [17-18-26].
Therefore, the extensive research pure H_2 as fuel has led to the development and successful marketing of hydrogen engine. For example, Ford developed P 2000 hydrogen engine, which was utilized to drive Ford's E-450 Shuttle Bus. BMW designed a 6 liter V-12 engine using liquid hydrogen as fuel this engine has a power out about 180 kW and at the torque of 340 Nm [17].

2.3 Abnormal combustion

The same properties that make hydrogen such a desirable fuel for internal combustion engines also bear responsibility for abnormal combustion events associated with hydrogen. The wide flammability limits, low required ignition energy and high flame speeds can result in undesired combustion phenomena generally summarized as combustion products. These include surface ignition and backfiring as well as auto ignition [22].The suppression of abnormal combustion in hydrogen has proven to be quite a challenge and measures taken to avoid abnormal combustion have important implications for design of an engine, mixture and load control. For SI engines, three regimes of abnormal combustion exist: knock (auto-ignition of the end gas region), pre-ignition (uncontrolled ignition induced by a hot spot, premature back flash, flashback, and induction ignition; this is a premature ignition during the suction stroke, which was observed as an early form of pre-ignition) and backfire. [23].

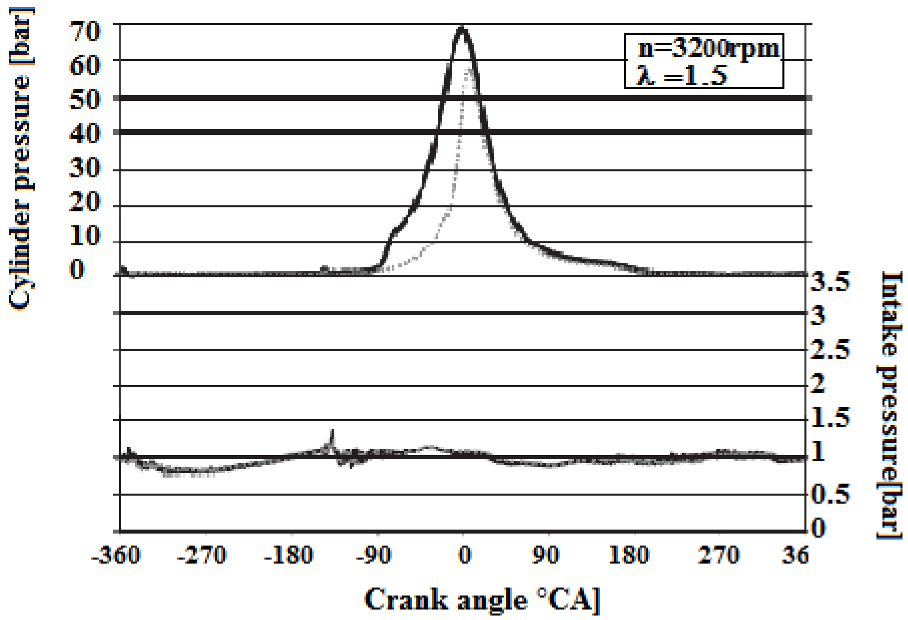

Fig.3. Typical cylinder and intake manifold pressure traces with pre-ignition (solid lines) [22]

2.4 Emissions

The combustion of hydrogen with oxygen produces water; the reaction takes place as;

$$2H_2 + O_2 = 2H_2O\ldots (2)$$

The combustion of hydrogen with air also produces oxides of nitrogen (NOx), as shown bellow,

$$2H_2 + O_2 + N2= H_2O + N_2 + NOx\ldots (3)$$

The oxides of nitrogen are created due to the high temperatures generated within the combustion chamber during the process of combustion. This high temperature is responsible for some of the nitrogen in the air to combine with the oxygen in the air. The amount of NOx formed depends on the air/fuel ratio, engine compression ratio, speed of an engine, ignition lag. In addition to NOx, traces of carbon monoxide and carbon dioxide can be present in the exhaust gas, due to fast oil burning in the combustion chamber.

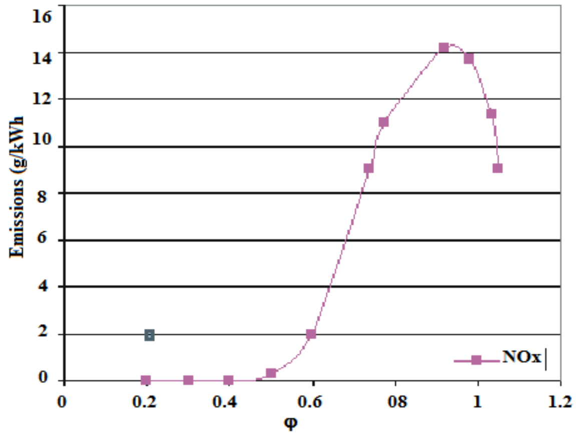

Fig.4. Emissions of a hydrogen engine.

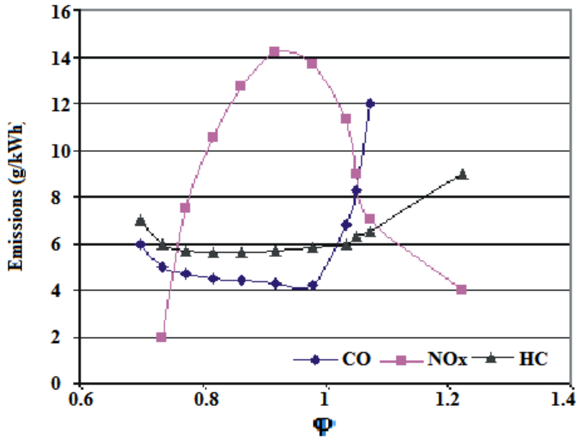

Fig.5. Emissions of a gasoline engine

2.5 Power Output

The theoretical maximum power of a hydrogen engine depends on the air/fuel ratio and fuel injection method. Stoichiometric air/fuel ratio for hydrogen is 34:1. With this air/fuel ratio, hydrogen will dislodge 29% of the combustion chamber leaving only 71% for the air. As a result, the energy content of this mixture will be less than it would be if the fuel were gasoline.

As in carbureted and port injection methods mix the fuel and air prior to it entering the combustion chamber, these Depending on the condition of the engine (burning of oil) and the operating strategy used (a rich versus lean air/fuel ratio), a hydrogen engine can produce from almost zero emissions (as low as a few ppm) to high NOx and significant carbon monoxide emissions. Figure 4 illustrates a typically NOx curve relative to phi (φ) for a H_2 engine. A graph of other emissions is shown in Figure 5 for gasoline.

Therefore, depending on how the quantity of fuel metered, the output power is maximum for a hydrogen engine can be either 15% higher or 15% less than that of gasoline if a chemically correct air/fuel ratio is used. At an air/fuel ratio, the temperature in combustion chamber is very high and as a result it will form a large amount of nitrogen oxides (NOx), which is a dangerous pollutant. Since one of the reasons for using hydrogen is that exhaust emissions is low, as the design of hydrogen engines are not run at a stoichiometric air/fuel ratio [6].

CONCLUSION

Hydrogen can be used in both spark ignition as well as compression ignition engines without any major modifications in the existing engine design. A well designed manifold injection system can tolerate any undesirable combustion phenomena such as backfire and sudden pressure rise.

The vehicle driven on internal combustion engine can possibly to operate on both petroleum products and with hydrogen. Because of hydrogen has a wide range of ignition feature, engine can be used without a throttle controller. Engine pumping losses can be reduced using this approach. Using direct injection of fuel eliminate the problem of pre-ignition occur in the intake manifold; it does not necessarily prevent pre-ignition within the combustion chamber.

An appropriate DI system design specifically on the basis of hydrogen's combustion characteristics for a particular engine configuration ensures smooth engine operational characteristics without any undesirable combustion phenomena.

Backfiring is limited to external mixture formation operation and can be successfully avoided with DI operation. A well design of an engine can largely reduce the phenomena of surface ignition. Ignition lag can also control the knock during high flow of hydrogen. Hydrogen engine shows the lean combustion process during operation.

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