

Analysis of a Hydrogen Fueled Internal Combustion Engine

Anand¹, Shakti Soni², Nakul Aggarwal³

^{1,2,3}Mechanical Engineering Department, Institute of Technology and Science, Bhiwani, India

ABSTRACT

In the history of internal combustion engine development, hydrogen has been considered at several phases as a substitute to hydrocarbon-based fuels. Starting from the 70's, there have been several attempts to convert engines for hydrogen operation. Together with the development in gas injector technology, it has become possible to control precisely the injection of hydrogen for safe operation. Since the fuel cell needs certain improvements before it is widely used in vehicles, the conventional internal combustion engine is to play an important role in the transition. This study examines the performance characteristics and emissions of a hydrogen fueled conventional spark ignition engine. Slight modifications are made for hydrogen feeding which do not change the basic characteristics of the original engine. Comparison is made between the gasoline and hydrogen operation and engine design changes are discussed. Certain remedies to overcome the backfire phenomena are attempted.

1. INTRODUCTION

Fossil fuels (i.e., petroleum, natural gas and coal), which meet most of the world's energy demand today, are being depleted rapidly. Also, their combustion products are causing global problems, such as the greenhouse effect, ozone layer depletion, acid rains and pollution, which are posing great danger for our environment, and eventually, for the total life on our planet. Many engineers and scientists agree that the solution to all of these global problems would be to replace the existing fossil fuel system with the clean hydrogen energy system. Hydrogen is a very efficient and clean fuel. Its combustion will produce no greenhouse gases, no ozone layer depleting chemicals, and little or no acid rain ingredients and pollution. Hydrogen, produced from renewable energy (solar, wind, etc.) sources, would result in a permanent energy system which would never have to be changed. Global utilization of fossil fuels for energy needs is rapidly resulting in critical environmental problems throughout the world. Energy, economic and political crises, as well as the health of humans, animals and plant life, are all critical concerns. There is an urgent need of implementing the hydrogen technology. A worldwide conversion from fossil fuels to hydrogen would eliminate many of the problems and their consequences. The production of hydrogen from non-polluting sources is the ideal way (Zweig RM. 1992).

Energy stored in hydrogen would be available at any time and at any place on Earth, regardless of when or where the solar irradiance, the hydropower, or other renewable sources such as biomass, ocean energy or wind energy was converted. The fundamental variations in the times and places of solar energy supply and human energy demands can be overcome using hydrogen. Solar hydrogen makes solar energy as storable and transportable as oil and natural gas are by nature, but without the burden of their negative environmental impact. Solar hydrogen combines the advantages of hydrocarbons (storability and transportability) with the advantages of solar energy (ecological acceptability, renewability and low risk). Solar hydrogen has no need for the carbon atom, which makes the hydrocarbons almost infinitely storable at room temperatures, but is also the reason for their negative ecological impact.

Hydrogen has long been recognized as a fuel having some unique and highly desirable properties, for application as a fuel in engines (King RO, Rand M. 1955). It is the only fuel that can be produced entirely from the plentiful renewable resource water, though through the expenditure of relatively much energy. The use of hydrogen as an engine fuel has been attempted on very limited basis with varying degrees of success by numerous investigators over many decades (Erren RA, Campbell WH. 1933), and much information about their findings is available in the open literature.. Moreover, the increasingly greater emphasis being placed on the nature of emissions and efficiency considerations often makes much of the very early

work fragmentary and mainly of historical value. Obviously, there is a need to be aware of what has been achieved in this field while focusing both on the attractive features as well as the potential limitations and associated drawbacks that need to be overcome for hydrogen to become a widely accepted and used fuel for engine applications.

LITERATURE SURVEY

In the early years of the development of internal combustion engines hydrogen was not the "exotic" fuel that it is today. Water splitting by electrolysis was a well known laboratory phenomenon. Otto, in the early 1870s, considered a variety of fuels for his internal combustion engine, including hydrogen. He rejected gasoline as being too dangerous. Later developments in combustion technology made gasoline safer. It was Rudolf A. Erren who first made practical the hydrogen-fueled engine in the 1920s and converted over 1,000 engines. His projects included trucks and buses. After World War II the allies discovered a submarine converted by Erren to hydrogen power. Even the torpedoes were hydrogen powered.

The Indian Institute of Technology tested spark ignition engines converted to hydrogen and has come to the following conclusions: Hydrogen permits a wide range of fuel-air mixtures. Very little throttling is needed. The fuel-air ratio and the amount of fuel are varied instead. Conversion requires higher compression ratios like up to 11:1. Hydrogen is 30 to 50% more efficient than gasoline. The Indian researchers also reached some conclusions regarding the use of hydrogen in addition to diesel fuel in diesel engines. They reduced the compression ratios from 16.5:1 to 14.5:1. Because of hydrogen's high rate of combustion only a small amount should be used mixed with diesel fuel. A high ignition temperature is necessary: 585 °C. The more hydrogen is added to the fuel mix the lower is the level of toxic emissions.

The Billings Energy Corporation in Independence, Missouri, converted a U.S. postal Jeep to hydrogen hydride. On gasoline it got 3.9 km/liter. The hydrogen fuel consumption is 4.9 km/liter per gasoline energy equivalent. This was an improvement of 24%. A special gaseous carburetor was used. High flame speed and low ignition energy required narrowing the spark gap. Problems of rusting and pitting on the sparkplug tip developed. Billings replaced the plugs with Champion stainless steel plugs to eliminate the problem. Rusted plug tips can cause preignition through the valves (backfire).

Since the firing rate was faster, they had to change the ignition timing on the inline six-cylinder engine. The researchers added a water injection system to lower the combustion temperature and nitrous oxide production. The ratio was 4:1, by weight, of water to hydrogen. Daily fuel consumption was 1.4 kg of hydrogen and 5.4 kg of water. Water was injected as a fine mist directly into the manifold of the engine. This reduced backfiring into the manifold and boosted power. The disadvantage of low pressure sequential gas injection is the low density of the gas. For smaller engines running at high speeds (traction application), the injectors have to deliver a high volume of gas in a very short time. Other problems may arise with the durability of the injectors and possible leaks.

2. THE SPARK IGNITION ENGINE AND HYDROGEN AS AN ENGINE FUEL

The spark ignition (SI) engine is one of the two most common reciprocating internal combustion (IC) engine types in current use. Basic SI engines have not fundamentally changed since the early 1900s with the possible exception of the introduction of the Wankel rotary SI engine in the 1960s. However, major advances in the areas of materials, manufacturing processes, electronic controls, and computer aided design have led to significant improvements in dependability, longevity, thermal efficiency, and emissions during the past decade. Electronic controls, in particular, have played a major role in efficiency gains in SI automotive engines through improved control of the fuel injection and ignition systems that control the combustion process. Electronic control of diesel fuel injection systems is also becoming more common and is producing improvements in diesel emissions and fuel economy.

Hydrogen, over wide temperature and pressure ranges, has very high flame propagation rates within the engine cylinder in comparison to other fuels. These rates remain sufficiently high even for very lean mixtures that are well away from the stoichiometric mixture region. The associated energy release is also so fast that the combustion duration, tends to be short and contributes towards producing high-power output efficiencies and high rates of pressure rise following spark ignition. The fast burning characteristics of hydrogen permit much more satisfactory high-speed engine operation. This would allow an increase in power output with a reduced penalty for lean mixture operation. Also, the extremely low boiling temperature of hydrogen leads to fewer problems encountered with cold weather operation.

Table 1. Physical properties of hydrogen, methane and gasoline

P r o p e r t y	H y d r o g e n	M e t h a n e	G a s o l i n e
Density at 1 atm and 300 K (kg / m ³)	0 . 0 8 2	0 . 7 1 7	5 . 1 3
Stoichiometric Composition in air (% by volume)	2 9 . 6 0	9 . 4 8	1 . 7 0
Number of moles after combustion to before	1 . 0	1 . 0 0	1 . 0 5 8
L H V (M J / k g)	1 2 0	4 6 . 7 2	4 4 . 7 9
Combustion energy per kg of stoichiometric mixture (MJ)	3 . 4 0	2 . 5 9	2 . 8 2

In the present work, a conventional 4 cylinder SI engine was adapted to operate on gaseous hydrogen. Compressed gas at 200 bar in steel bottles was introduced to the engine by external mixing. The first stage regulator drops the pressure to 3 bar to a copper gas supply line where a flowmeter is installed. The second stage regulator supplies hydrogen to the mixing apparatus installed on the inlet manifold. Spray nozzles for water induction are placed approximately 4 cm away from the inlet valves. Ignition timing was set to 10° before TDC and fixed.

3. Experimental Setup and Methodology

The laboratory consists of test banks involving water (Froude) and eddy current type dynamometers, exhaust emission analyzers, fuel metering devices and support equipment. The dynamometer and supporting electrical equipment were calibrated a few days before the tests began. To avoid temperature and pressure variations as far as possible, experiments with gasoline were immediately followed by hydrogen experiments with the engine already warmed up to operating temperature. Compressed hydrogen at 200 bar from 50 l steel bottles was dropped down to 3 bar in the first stage regulator. The fuel line is a copper tube connected to a hydrogen flowmeter. The second stage regulator supplies the gaseous hydrogen to the mixer according to the inlet manifold pressure. The engine is coupled to the dynamometer with its gearbox. The 4th gear has a ratio of 1:1 so the rotational speed measured at the dynamometer is exactly the same as the engine speed. Besides the engine itself; flywheel, starting motor, alternator, fuel pump, fuel tank, dashboard assembly and exhaust assembly are mounted to the required parts and places. At the exhaust outlet, there is a standard muffler and a final silencer muffler. Exhaust temperature was measured between the two muffler positions and emission values were obtained just after the final silencer.

Table 2: Engine Technical Specifications

Make/Model	FIAT licensed 124 by TOFAŞ
Bore	7 3 . 0 m m
S t r o k e	7 1 . 5 m m
V a l v e s (O H V)	8 v a l v e s (O H V)
S w e p t V o l u m e	1 1 9 7 c c
C o m p r e s s i o n R a t i o	8 . 8 : 1
P o w e r	60 HP(DIN) at 5600rpm
T o r q u e	89 Nm at 3400 rpm

The engine is coupled with its original shaft to the dynamometer. The control panel of the dynamometer is placed at a safe distance from the setup but is easily accessible. Ambient pressure and temperature as well as engine speed and torque values are easily read from the large size gauges. Load is varied by two knobs that change the current in the stator of the eddy current dynamometer. Basically three types of loading are possible, constant speed, variable speed and a combination

of these. A 3-way switch is installed on the dashboard assembly that allows immediate switching from gasoline to hydrogen. This switch controls the solenoid valves on the gasoline line and hydrogen regulator. In this way, switching between fuels is possible without stopping the engine.

4. Important Engine Characteristics

An engine's primary factors that are important to its user are its performance over the operating range, its fuel consumption within the operating range and the cost of the fuel, the engine's noise and air pollutant emissions, its initial cost and the durability as well as reliability throughout its operating life. Geometrical relationships and other parameters characterize an engine. Engine performance, efficiency and emission characteristics are the most common considerations. Engine performance is more precisely defined by the maximum power at rated speed and maximum torque at rated speed. Rated speed is the speed at which these maximum values are reached. In general the rated speed for maximum power is close to the engines maximum allowable speed whereas the maximum torque is developed around or slightly above the half of maximum operating speed.

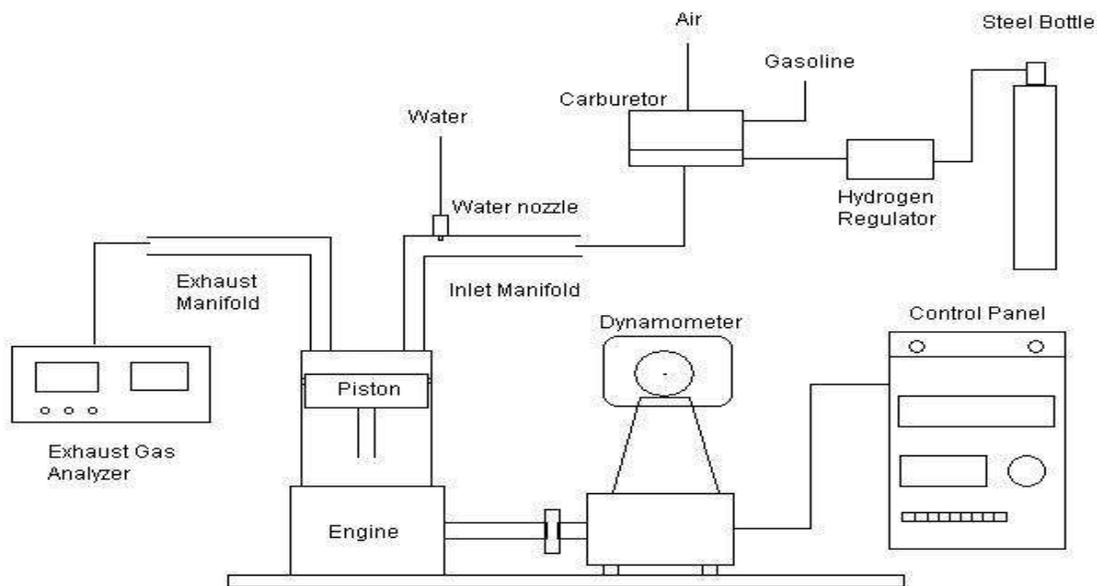


Figure 1: Schematic of the experimental setup

5. Result and Discussion

For the purpose of detailed analysis, as many as possible operating points were recorded. Much experimentation has been done to avoid backfire. Firstly the mixer was placed above the throttle valve, level with the air filter housing. In this arrangement the engine's tendency to backfire was considerably high. For this reason it was placed between the carburetor body and inlet manifold afterwards. At idling and no load speeds, no backfire occurred. When load was applied, a practical limit of about 20 Nm prevented further loading no matter how much water was given as a fine mist into the inlet manifold.

5.1. Preignition and Backfire

Hydrogen burns quickly and has a low ignition temperature. This may cause the fuel to be ignited by hot spots in the cylinder before the intake valve closes. It may also cause backfire, preignition, or knock. These problems are particularly more with high fuel-air mixtures. Uncontrolled preignition resists the upward compression stroke of the piston, thereby reducing power. Remedies for backfire include: timed port injection, delayed injection to make sure the fuel detonates only after the intake valve is closed; water injection, 1.75 water to hydrogen, by weight (Peavey 2003). An appropriately designed timed manifold injection system can overcome the problems of backfiring in a hydrogen engine.

5.2 Performance Parameters

The term performance usually means how well an engine is doing its work in relation to the input energy or how effectively it provides useful energy in relation to some other comparable engines. Sample calculation for power, thermal efficiency and mean effective pressure is as follows: For 3000 rpm,

5.2.1 Power

Due to its low energy content per unit volume, an externally mixed hydrogen engine has less power than a conventional gasoline fueled engine. This drawback can be overcome by supercharging. In this way more air can be charged in the cylinder and more fuel as well. It also helps to cool down the cylinder avoiding preignition.

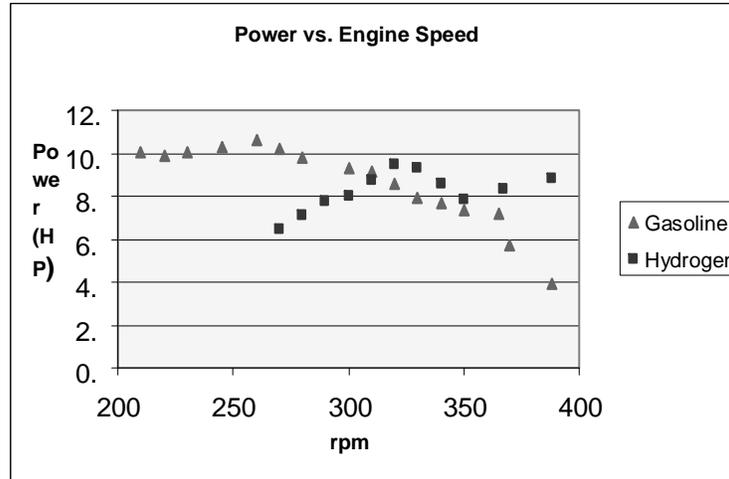


Figure 2: Power vs. Engine Speed

5.2.2 Brake thermal efficiency

Obviously hydrogen has a higher brake thermal efficiency. It is known for gasoline engines that they show their effective efficiency at greater part loads whereas hydrogen can operate even at low part loads with better efficiency.

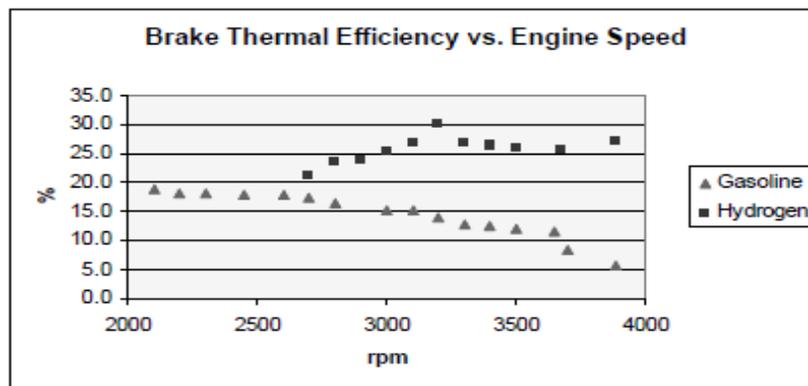


Figure 3: Brake thermal efficiency vs. Engine Speed

5.2.3 Brake mean effective pressure

Again at speeds below 3000 rpm the gasoline engine is more effective. Hydrogen operation shows a slightly better effectiveness at speeds above 3200 rpm.

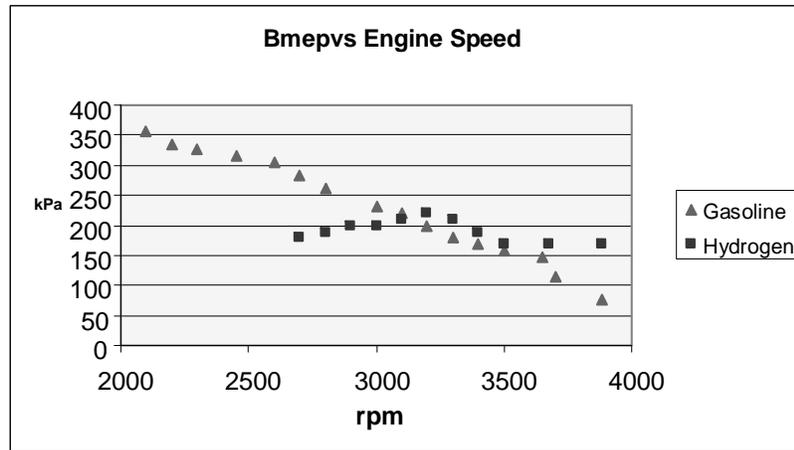


Figure 4: Brake mean effective pressure vs. Engine Speed

5.3 Emission Parameters

Temperature analysis of the exhaust gas can be made in Figure 4. As soon as the hydrogen engine gets into the high speed range, the exhaust temperature starts to increase significantly. The cooling effect of water that is added with hydrogen is observed. But fast burning that occurs at increased speed during hydrogen operation results in temperature rise.

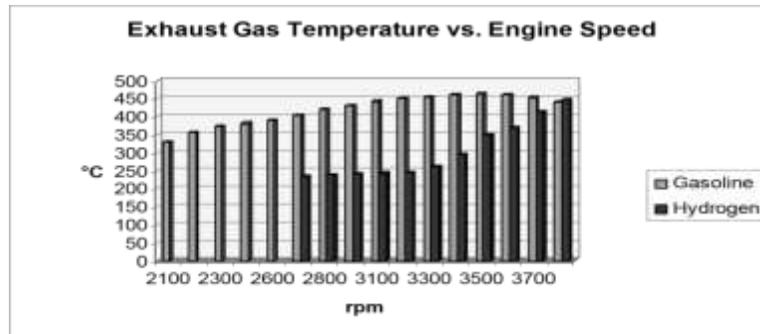


Figure 4. Exhaust gas temperature of gasoline and hydrogen engine

Figure 5. Portrays the NO_x levels of both engines in ppm. Significant decrease in NO_x emissions is observed with hydrogen operation. Almost a 10-fold decrease can easily be noted. The cooling effect of the water inducted plays an important role in this reduction. Also operating the engine with a lean mixture kept the emissions low.

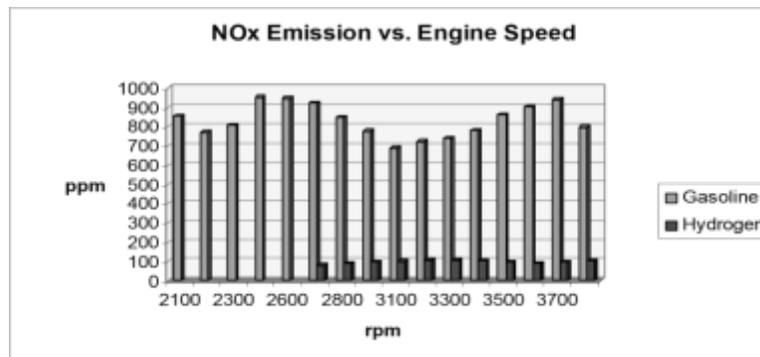


Figure 5: NOx Emission vs. Engine Speed

Although more air than required for complete combustion is present in the cylinder (fuel lean operation), the engine is not capable of burning the total amount of fuel. Carbon monoxide emissions are due to incomplete combustion of fossil fuels. It is expected that the hydrogen engine has zero carbon monoxide emissions since hydrogen is a carbon-free fuel. As the

results in Figure 6. show, some amount of carbon monoxide is still present even with hydrogen. This is due to the burning of the lubricating oil film inside the cylinder. As speed increases, these emissions tend to diminish.

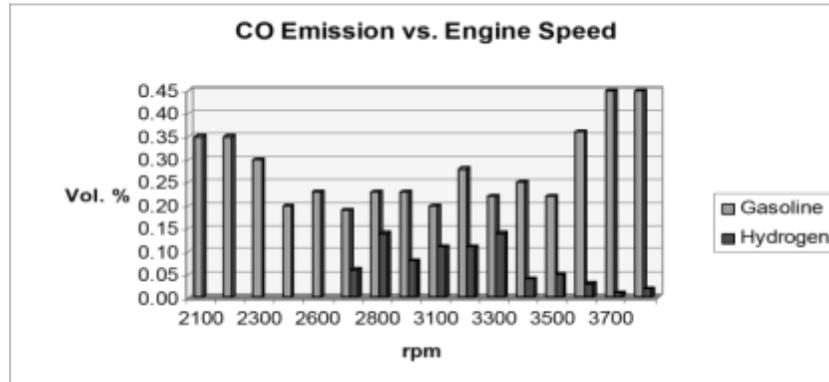


Figure 6. CO Emission vs. Engine Speed

For hydrogen there is practically no emission, only very slight values again due to combustion of the lubricating oil film. During combustion the temperature inside the cylinder is extremely high. As the piston expands, this heat evaporates a certain amount of the oil. Observing Figure 8. the contribution of the evaporated and incompletely burned oil to the overall emission can be guessed. Gasoline is a long-chain hydrocarbon and when not completely burned, breaks up into short chain hydrocarbons. Hydrogen is a gaseous fuel and does not dissolve the oil film on the cylinder walls. This is another advantage of it against conventional fuels. Better lubricating characteristics and longer engine life is obtained. At low speed the gasoline engine is choked and therefore more unburnt hydrocarbons are present in the exhaust gases. The only hydrocarbon emission from the hydrogen engine is due to the above mentioned oil film evaporation.

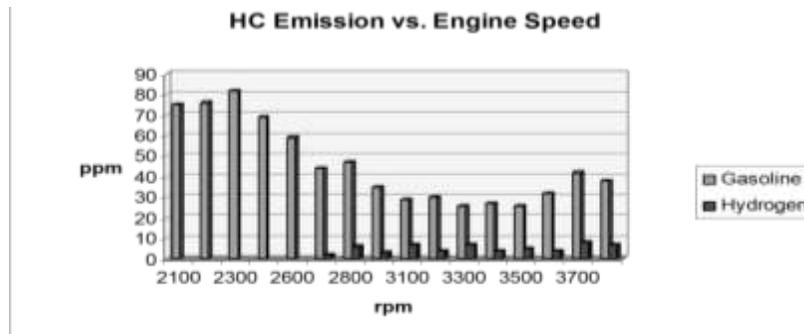


Figure 8. HC Emission vs. Engine Speed

Conclusions

A conventional 4 cylinder SI engine was adapted to operate on gaseous hydrogen. Compressed gas at 200 bar in steel bottles was introduced to the engine by external mixing. The first stage regulator drops the pressure to 3 bar to a copper gas supply line where a flowmeter is installed. The second stage regulator supplies hydrogen to the mixing apparatus installed on the inlet manifold. Spray nozzles for water induction are placed approximately 4 cm away from the inlet valves. Ignition timing was set to 10° before TDC and fixed.

First tests were performed with the mixer installed on top of the carburetor body. This is the usual configuration in propane mixing. Serious backfire was observed with this installation. Another mixer was then put between the carburetor body and inlet manifold. Backfire was prevented in this option. Under no-load condition, the engine operated flawless with a smooth idling. When load is applied and engine speed is below 2600 rpm, serious backfire occurred and caused a sudden drop in engine power. Water mist from the spray nozzles greatly enhances the backfire-safe operation.

Specific features of the use of hydrogen as an engine fuel were analyzed. Results of the tests demonstrated that there will be

power loss for the low speed operation whereas high speed characteristics could compete with gasoline performance. The increase in thermal efficiency was obvious. It has been proved that hydrogen is a very bright candidate as an engine fuel. NO_x emissions were about 10 times lower than with gasoline operation. CO and HC emissions were almost negligible as expected. Traces of these emissions were present because of the evaporating and burning lubricating oil film on the cylinder walls.

Combustion properties of hydrogen favor fast burning conditions such as in a high speed engine. Design changes that would allow the engine to greater speeds would have a beneficial effect. Appropriate changes in the combustion chamber together with better cooling of the valve mechanism, would increase the possibility of using hydrogen across a wider operating range.

Sequential injection of gaseous hydrogen instead of carburetion could greatly solve the backfire problem. Better performance could be obtained. Even further, liquid hydrogen either internally mixed or injected into the manifold could be a measure against backfire due to its extraordinary cooling effect (20 K temperature).

An electronic control unit that measures the speed, and varies the injection timing together with ignition timing installed on a supercharged, intercooled, high compression ratio, short stroke and high speed engine seems to be the most appropriate way to get the best from hydrogen's unique properties.

Hydrogen has the potential to achieve problem-free operation in IC engines. The future advances depend on whether hydrogen can be obtained abundantly and economically.

REFERENCES

- [1]. Veziroglu TN. 1987, International Journal of Hydrogen Energy 12:99 INSPEC Compendex.
- [2]. Winter CJ. 1987, International Journal of Hydrogen Energy 12:521 INSPEC Compendex.
- [3]. Serpone N, Lawless D, Terzian R. 1992, Solar Energy 49:221 INSPEC Compendex.
- [4]. Zweig RM. 1992, Proceedings of the Ninth World Hydrogen Energy Conference. Paris (France) :1995.
- [5]. Rever B. 2001, Renewable Energy World, Review Issue 2001–2002 ed. by James x James, vol.4, no 4, p177.
- [6]. Gretz J. 1992, Proceedings of the Second World Renewable Energy Congress. Reading (England) :2438.
- [7]. Block DL, Veziroglu TN. 1994, Hydrogen energy progress X, Proceedings of the Tenth World Hydrogen Energy Conference. Cocoa Beach (Florida, U.S.A.), Foreword.
- [8]. King RO, Rand M. 1955, "The hydrogen engine" Canadian Journal Technology 33:445–69.
- [9]. Erren RA, Campbell WH. 1933, "Hydrogen a Commercial fuel for internal combustion engines and other purposes" J Inst Fuel 1933; 6:277–90.
- [10]. Cox KE, Williamson KD. 1977, "Hydrogen: its technology and implications" Vols. I–V Boca Raton, FL: CRC Press.
- [11]. Peavey MA. 2003, "Fuel from Water: Energy Independence with Hydrogen", (Merit Products) 11th Edition p. 135-137.
- [12]. Sierens R, Rosseel E. 1995. "Development of a multi-point timed injection S.I. natural gas engine" ASME Spring Engine Technology Conference, Marietta (Ohio).
- [13]. ICE, vol. 24, Natural Gas and Alternative Fuels for engines, p. 99–104.
- [14]. Sierens R, Rosseel E. 1995. "Sequential injection of gaseous fuels", Proceedings of the Fifth International EAEC Congress, Strasbourg, June, Paper No SIA 9506A03. p. 10.
- [15]. Sierens R, Rosseel E. 1998 "Variable composition hydrogen-natural gas mixtures for increased engine efficiency and decreased emissions".