

**ANALYSIS OF A HYDROGEN FUELED  
INTERNAL COMBUSTION ENGINE**

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**by  
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## **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.

## ÖZET

Hidrojenin alternatif yakıt olarak içten yanmalı motorlarda kullanılması fikri 1970'lere dayanmaktadır. Bir yeraltı kaynağı olan fosil yakıtların aşırı kullanım sonucu yakın gelecekte tükeneceği endişesi, araştırmacıları bu temiz ve yenilenebilir yakıtı yöneltmiştir. Sudan elde edilebilirliği, çevre dostu olması ve geleneksel yakıtlara göre avantajları bulunması hidrojenin gözde enerji kaynağı olma yolunda önemli bir yere gelmesine neden olmuştur. Yakıt hücresi teknolojisindeki gelişmeler halen olgunlaşma aşamasında olduğundan, hidrojenin içten yanmalı motorlarda kullanılması, geleneksel yakıtlardan hidrojene geçiş sürecinde kayda değer potansiyele sahip gözükmektedir. Bu çalışmada bir benzin motoru hidrojene uyarlanarak motor performans ve egzoz emisyon değerleri karşılaştırılmıştır. Alev geri tepme sorununu gidermek için çalışmalar yapılmıştır. Hidrojenin yanma özelliklerinden tam verim alabilmek için motorda gerekli dizayn değişiklikleri tartışılmıştır.

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# NOMENCLATURE

SI	Spark ignition
IC	Internal combustion
CI	Compression ignition
TDC	Top dead center
BDC	Bottom dead center
ECU	Electronic control unit
EEPROM	Electrically erasable programmable read-only memory
CO	Carbon monoxide
CO <sub>2</sub>	Carbon dioxide
HC	Hydrocarbon
NO	Nitric oxide
NO <sub>2</sub>	Nitrogen dioxide
NO <sub>x</sub>	Sum of NO and NO <sub>2</sub>
ppm	Parts per million
A/F	Air fuel ratio
F/A	Fuel air ratio
T	Torque (Nm)
F	Force (N)
b	Distance (m)
P	Power (kW or HP)
P <sub>b</sub>	Brake power (kW or HP)
$\omega$	Rotational speed (rev/s)
mep	Mean effective pressure (kPa)
bmep	Brake mean effective pressure (kPa)
sfc	Specific fuel consumption (g/kW-h or g/HP-h)
bsfc	Brake specific fuel consumption (g/kW-h or g/HP-h)
$\dot{m}_a$	Air mass flow rate (kg/s)
$\dot{m}_f$	Fuel mass flow rate (kg/s)
Q	Heating value (MJ/kg)
$\eta$	Efficiency
$\phi$	Equivalence ratio (fuel air equivalence ratio)

$\lambda$	Relative air fuel ratio
LHV	Lower heating value
NTP	Normal temperature and pressure
OHV	Overhead valve
NDIR	Non-dispersive infra-red
$V_d$	Volume displaced ( $\text{dm}^3$ )

#### Subscripts

b	Brake
bth	Brake thermal
f	Fuel
a	Air
LHV	Lower heating value
s	Stoichiometric
d	Displaced

# CHAPTER 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.

Fossil fuels possess very useful properties not shared by non-conventional energy sources that have made them popular during the last century. Unfortunately, fossil fuels are not renewable (Veziroglu TN. 1987). In addition, the pollutants emitted by fossil energy systems (e.g. CO, CO<sub>2</sub>, C<sub>n</sub>H<sub>m</sub>, SO<sub>x</sub>, NO<sub>x</sub>, radioactivity, heavy metals, ashes, etc.) are greater and more damaging than those that might be produced by a renewable based hydrogen energy system (Winter CJ. 1987). Since the oil crisis of 1973, considerable progress has been made in the search for alternative energy sources. A long term goal of energy research has been the seek for a method to produce hydrogen fuel economically by splitting water using sunlight as the primary energy source. Much fundamental research remains to be done (Serpone N, Lawless D, Terzian R. 1992).

Lowering of worldwide CO<sub>2</sub> emission to reduce the risk of climate change (greenhouse effect) requires a major restructuring of the energy system. The use of hydrogen as an energy carrier is a long term option to reduce CO<sub>2</sub> emissions. However, at the present time, hydrogen is not competitive with other energy carriers.

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).

The amount of solar energy reaching the Earth is enough to supply mankind with many thousand times the energy it presently requires. This energy supply is, however, neither constantly available nor distributed equally over the surface of the globe. Indeed, the places where mankind's energy consumption is highest are not the places where the Sun's irradiance is at a maximum. If the Sun's daytime energy supply also has to be used at night or its summer supply also in the winter, if the solar energy available at places with high insulation is also needed at places with low insulation and large energy demands, then it is physically impossible to meet these needs directly with the primary energy of solar irradiance. Solar hydrogen is a clean energy carrier. Electrolytic hydrogen is made from water and becomes water again. Hydrogen obtained from solar energy is ecologically responsible along its entire energy conversion chain. At only one link of the chain can a pollutant, nitrogen oxide, arise; and this occurs only if the hydrogen is not combined with pure oxygen, but using air as an oxidant, such as in reciprocating piston engines or gas turbines of automobiles or aircraft. At the high reaction temperatures which arise in such places, the oxygen and nitrogen in the air can combine to form nitrogen oxide.

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.

The worldwide photovoltaics market has grown rapidly in recent years, a growth that will continue in many areas, especially as grid-connected PV applications (Rever B. 2001). Hydrogen is a carbon-free fuel which oxidizes to water as a combustion product.

The generated water becomes, together with renewable primary energy for splitting it, a source of clean and abundant energy in a carbon-free, natural cycle (Gretz J. 1992). In the development of all new energy options, hydrogen necessarily will play an important role because of its ability to supplement any energy stream and apply to any load. Hydrogen will act as a solar energy storage medium and transform solar energy into a transportation fuel (Block DL, Veziroglu TN. 1994).

The economies of rich nations and the lifestyle of most of their residents depend on cars and light trucks. These vehicles contribute most of the carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), volatile organic compounds (hydrocarbons, HC), and nitrogen oxides (NO<sub>x</sub>) emitted in cities. It is clear that motor vehicles are important to the economy and lifestyle. Importance goes well beyond the direct consumer expenditures and indirect (support) expenditures, such as roads, suburbs, oil wells, refineries, and service stations.

Technology developments have created several challengers to the gasoline powered, internal combustion engine (ICE) vehicle. Short of some wonderful new technology emerging, the evolving gasoline fueled ICE will continue to be the choice of consumers and automakers. Even with regulatory pressure, it is doubtful that any technology would displace the gasoline fueled ICE—at least not by 2020 or 2030. Perhaps, the only market signal that would make a new technology more attractive would be a large increase in gasoline prices. For example, \$3 per liter gasoline would encourage people to buy diesel or ethanol powered vehicles, perhaps in conjunction with a hybrid-electric technology. At \$1.50 per liter, these alternatives have a tiny market share. The search for new technologies and fuels is driven by regulators, not the marketplace. The important gaps between the goals of society and those of individual manufacturers and drivers have been a major justification for government regulation. Regulators are mandating increasingly strict standards for emissions of air pollutants, the ability to use alternative fuels, and there is a warning of more strict fuel economy standards. In addition to the concern for improving local air quality, regulators are concerned about lowering emissions, dependence on imported petroleum, and switching from petroleum to a more sustainable fuel. Regulators can penalize, or even prevent automakers from selling undesirable vehicles (no cars are produced within the EU countries that are not equipped with a catalytic converter) or fuel suppliers from selling undesirable fuels, but it is difficult to force consumers to buy what regulators consider to be desirable vehicles and fuels. Consumer appeal could lead to new propulsion

systems or fuels, but consumers are generally satisfied with what they have now. For consumers to view new engines and fuels as more desirable, technology would have to produce superior performance and economy in these alternatives, or the current fuels would have to be seen as less desirable due, for example, to high greenhouse gas emissions. The greatest force for change is the action taken by government, from providing roads to regulating the effects of each alternative. Social goals influence what products are allowed on the market and how they are regulated. If a consumer chooses a vehicle that is made of plenty of raw materials and fuel, the consumer may be using resources that otherwise would be available to enhance the well-being of future generations. Government actions are required to enable this technology by, for example, building roads or banning tetraethyl lead in gasoline. However, both automakers and regulators need to recognize the delicate balance between producing a product that is desired by consumers and having that product satisfy social goals as well. Alternative fuels have the potential to solve many of the current social problems and concerns, from air pollution and global warming to other environmental improvements and sustainability issues. It is not a foregone conclusion that alternative fuels will throw aside advanced gasoline ICE vehicles within 30 years.

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. Its combustion in oxygen produces uniquely only water but in air it also produces some oxides of nitrogen. These features make hydrogen an excellent fuel to potentially meet the ever increasingly strict environmental controls of exhaust emissions from combustion devices, including the reduction of green house gas emissions. Hydrogen as a renewable fuel resource can be produced through the expenditure of energy to replace increasingly the depleting sources of conventional fossil fuels. A brief statement and discussion of the positive features of hydrogen as a fuel and the associated limitations that are raising difficulties in its wide application as an engine fuel are both necessary and needed. Hydrogen gas has been in wide use as a fuel for quite a long time (Erren RA, Campbell WH. 1933). Additionally, enormous quantities of hydrogen are used increasingly as a raw material in a wide range of applications in the chemical industry, particularly in the upgrading of conventional fuel resources (Cox KE, Williamson KD. 1977). The viability of hydrogen as a fuel in general and in engine applications in particular, is critically dependent on the

effective, economic and satisfactory solution of a number of remaining key limiting problems. These limitations that hinder its widespread application as an engine fuel are primarily related to its production, storage, portability, transport and purity. These limitations can be considered to be far more serious than those facing the current and future applications of other fuels, including natural gas.

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. However, these reported performance data do not display consistent agreement between various investigators. There is also a tendency to focus on results obtained in specific engines and over narrowly changed operating conditions. 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. Also, there is a need to indicate practical steps for operating and design measures to be developed and incorporated for hydrogen to achieve its full potential as an attractive and superior engine fuel.



## CHAPTER 2

### LITERATURE REVIEW

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.

Most early engine experiments were designed for burning a variety of gases, including natural gas and propane. When hydrogen was used in these engines it would backfire. Since hydrogen burns faster than other fuels, the fuel-air mixture would ignite in the intake manifold before the intake valve could close. Injected water controlled the backfiring. Hydrogen gave less power than gasoline with or without the water.

During World War I hydrogen and pure oxygen were considered for submarine use because the crew could get drinkable water from the exhaust. Hydrogen was also considered for use in powering airship engines. The gas used for buoyancy could also be used for fuel. Even if helium were used to provide lift, hydrogen gas could be used to supply additional buoyancy if stored at low pressure in a light container.

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.

In 1924 Ricardo conducted the first systematic engine performance tests on hydrogen. He used a one cylinder engine and tried various compression ratios. At a compression ratio of 7:1, the engine achieved a peak efficiency of 43%. At compression ratio of 9.9:1, Burnstall obtained an efficiency of 41.3% with an equivalency ratio range of 0.58-0.80.

After World War II, King found the cause of preignition to be hot spots in the combustion chamber from the high temperature ash, the residue from burned oil and dust. He traced backfire to high flame velocity at high equivalency ratios.

M.R. Swain and R.R. Adt at the University of Miami developed modified injection techniques with a 1,600 cm<sup>3</sup> Toyota engine with a compression ratio of 9:1. The Illinois Institute of Technology converted a 1972 Vega using a propane carburetor. Converting to propane fuel utilizes similar technology as hydrogen.

Roger Billings, in collaboration with Brigham Young University, entered a hydrogen-converted Volkswagen in the 1972 Urban Vehicle Competition. The vehicle won first place in the emissions category over 60 other vehicles even though the peak emissions were greater than for other hydrogen powered vehicles elsewhere. Nitrous oxides exceeded levels obtained by other experimenters using direct injection.

Robert Zweig converted a pickup truck to hydrogen power in 1975. It has been running ever since. He solved the backfiring problem by using an extra intake valve to admit hydrogen separately from air. It is a simple, elegant vehicle that uses compressed hydrogen. The American Hydrogen Association displays the Zweig hydrogen pickup trucks in public exhibits.

The Brookhaven National Laboratory converted a Wankel (rotary) engine to hydrogen. It worked better with hydrogen than conventional engines because its combustion chamber enhances the emission of hydrocarbon pollutants.

Mazda has converted one of their rotary engine cars to run on hydrogen. The unique design of the rotary engine keeps the hydrogen and air separate until they are combined in the combustion chamber.

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.

In experiments in 1980 with a diesel engine converted to run on 100% hydrogen, the U.S. Bureau of Mines, in collaboration with EIMCO Mining Machinery, found that the nitrous oxide emissions for hydrogen is one-tenth of the amount for the same vehicle on diesel. With hydrogen, the only other emission was water vapor. This is important for vehicles operating in mines and other confined spaces.

They mounted a 63.4 kW (85 hp) engine on a 4,500 kg truck. The diesel engine required the addition of spark ignition. Compression alone would not ignite the hydrogen at the reduced compression ratio. They added a turbocharger to increase the density of the incoming fuel.

The fuel induction system provides two intake paths; one for hydrogen and one for air. The fuel and air are kept separate until entering the cylinder to prevent backfiring (Peavey M. A. 2003).

The Laboratory of Transporttechnology (University of Gent, Belgium) has specialized in alternative fuels for the past 10 years or so. Natural gas, LPG, hythane and hydrogen have been the subject of extended research. In a first stage, a Valmet 420D engine, a natural aspirated diesel engine with direct injection was converted to a spark ignited engine for the use of hydrogen. This engine was used mainly for the development of a multipoint timed injection system and the study of different types of electromagnetic gas injectors (Sierens R, Rosseel E. 1995). The tests showed several

shortcomings of the then available gas injectors: leakage, unequal response time (opening delay) and low durability. In the mean time however, the research on gaseous injection systems (natural gas, LPG, etc.) has been increased enormously by the specialized companies and these problems are largely solved now.

A second engine, a GM-Crusader V8, was then converted for hydrogen use. The first tests were done with a gas carburetor, which allowed testing with hydrogen, natural gas and hydrogen-natural gas mixtures (hythane), (Sierens R, Rosseel E. 1998). In order to obtain a better control of the combustion process, the engine was then equipped with a sequential timed multipoint injection system. Such an injection system, as applied to liquid fuels (gasoline, liquid LPG, etc.) has several advantages including the possibility to tune the air-fuel ratio of each cylinder to a well-defined value, increased power output and decreased cyclic variation of the combustion process in the cylinders. Timed injection also has an additional benefit for a hydrogen fueled engine, as it implies a better resistance to backfire (explosion of the air-fuel mixture in the inlet manifold). In nearly all cases, backfire-safe operation implies a limitation of the operation region of the air-fuel mixture on the “rich” side, thus for high load conditions. This restriction is decreased by the use of a multi-point sequential injection system. Direct injection in the combustion chamber, cryogenic storage (liquid hydrogen tank) and pump is even better, but not technically available for mass production (Furuhama S. 1995). All these advantages are well known (Sorusbay C, Veziroglu TN. 1988, Kondo T, Hiruma M, Furuhamas S. 1996, Lee ST, Yi HS, Kim ES. 1995, Guo LS, Lu HB, Li JD. 1999).

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.

The German Aerospace Research Establishment (DLR) used cryogenic hydrogen with hybrid mixture formation on a BMW 745i vehicle in a joint effort with BMW. The cryogenic characteristics of hydrogen like high range per tank filling and low amount of mass for storage favor its use together with the cooling effect that occurs during external mixing. Satisfactory achievements were made by hybrid mixture formation, a proper combination of both internal and external mixture formation, in means of power and torque characteristics under steady and intermittent operating conditions. (Peschka W. 1998)

## CHAPTER 3

### THE SPARK IGNITION ENGINE

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.

IC engines may be classified by a wide variety of characteristics, the primary ones being SI vs. CI, four-stroke vs. two-stroke, and reciprocating vs. rotary. Other possible categories of classification include intake type (naturally aspirated vs. turbocharged or supercharged), number of cylinders, cylinder arrangement (in-line, V-type, opposed), cooling method (air vs. water), fueling system (injected vs. carbureted), valve gear arrangement (overhead cam vs. pushrod), type of scavenging for two-stroke engines (cross, loop, or uniflow), and type of injection for diesel engines (direct vs. indirect).

#### 3.1 Spark Ignition Engine Operation

Figure 3.1 is a cross-section schematic of a four-stroke SI engine. The SI engine relies on a spark plug to ignite a volatile air-fuel mixture as the piston approaches top dead center (TDC) on the compression stroke. This mixture may be supplied from a carburetor, a single throttle-body fuel injector, or by individual fuel injectors mounted in the intake port of each cylinder. One combustion cycle involves two revolutions of the crankshaft and thus four strokes of the piston, referred to as the intake, compression,

power, and exhaust strokes. Intake and exhaust valves control the flow of mixture and exhaust gases into and out of the cylinder, and an ignition system supplies a spark-inducing high voltage to the spark plug at the proper time in the cycle to initiate combustion. On the intake stroke, the intake valve opens and the descending piston draws a fresh combustible charge into the cylinder. During the compression stroke, the intake valve closes and the fuel-air mixture is compressed by the upward piston movement. The mixture is ignited by the spark plug, typically somewhat before TDC. The rapid premixed homogeneous combustion process causes a sharp increase in cylinder temperature and pressure that forces the piston down for the power stroke. Near bottom dead center (BDC) the exhaust valve opens and the cylinder pressure drops rapidly to near atmospheric. The piston then returns to TDC, expelling the exhaust products. At TDC, the exhaust valve closes and the intake valve opens to repeat the cycle again.

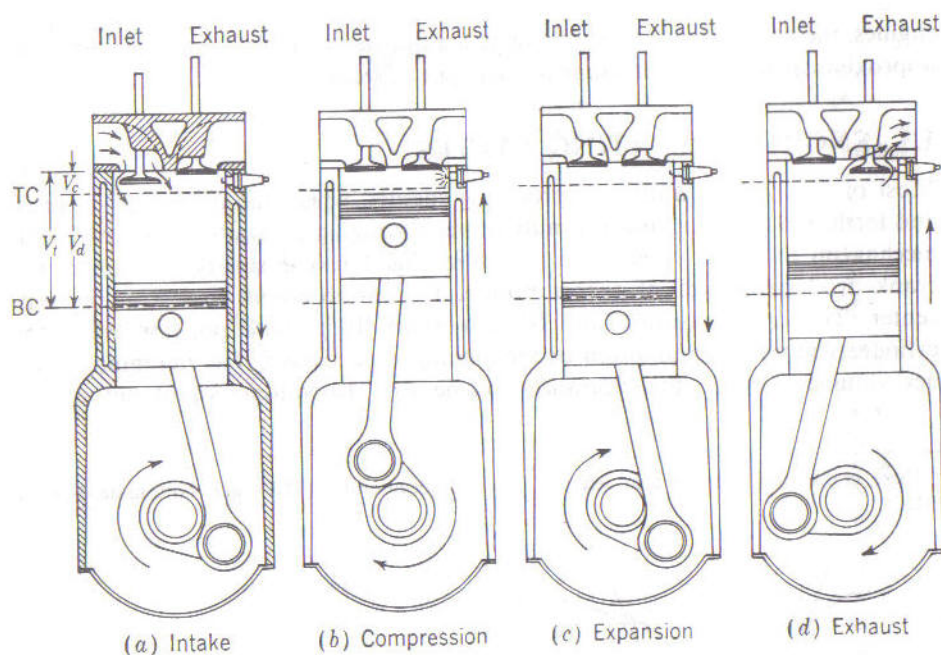


Figure 3.1. Schematic of a 4-stroke engine (Source: Heywood 1998)

In SI engines the air and fuel are usually mixed together in the intake manifold using either a carburetor or fuel injection system. In automobile applications, the temperature of the air entering the intake system is controlled by mixing ambient air with air heated by the exhaust manifold. For gasoline the ratio of mass flow of air to mass flow of fuel must be held around 15 to ensure reliable combustion. The carburetor meters an appropriate fuel flow for the engine air flow in the following manner. The air

flow through the venturi (a converging-diverging nozzle) sets up a pressure difference between the venturi inlet and throat which is used to meter an appropriate amount of fuel from the float chamber. Just below the venturi is a throttle valve or plate which controls the combined air and fuel flow as shown in Figure 3.2.

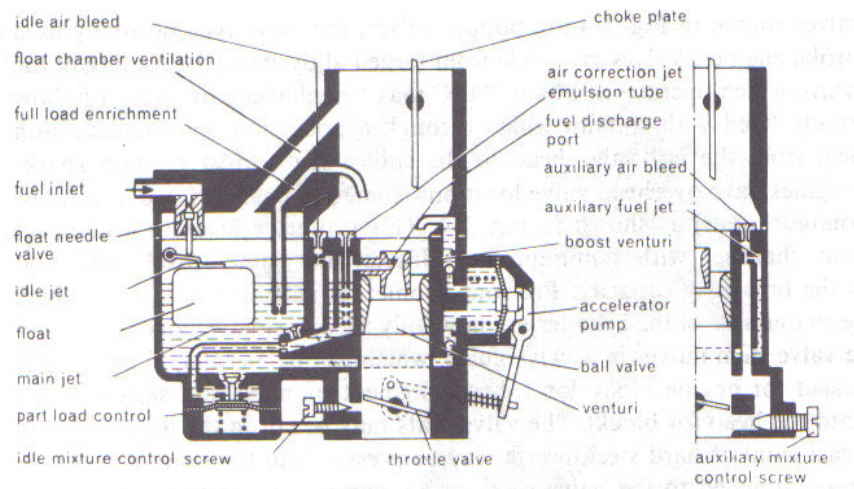


Figure 3.2. Cross section of a single barrel carburetor (Source: Heywood 1998)

The intake flow is throttled to below atmospheric pressure by reducing the flow area according to the power required. The maximum power is obtained when the throttle is wide open. The intake manifold is usually heated to promote faster evaporation of the liquid fuel thus obtaining a more uniform fuel distribution

Fuel injection into the intake manifold or inlet port is a widely used alternative to a carburetor. With port injection, fuel is injected through individual injectors from a low-pressure fuel supply into each intake port. There are several different types of injection systems. Mechanical injection in which an injection pump driven by the engine continuously injects fuel to the inlet port and electronically controlled injection where an electronic control unit (ECU) measures the air flow rate and accordingly supplies fuel. Figure 3.3. shows an electronically controlled system where the air flow rate is metered directly; the ECU actuates the injection valves by pulses whose durations are predefined and recorded in the ECU's EEPROM. Another alternative is the use of a single fuel injector located above the throttle plate in the position normally occupied by the carburetor. This approach gives the electronic control at reduced cost but also reduced accuracy.

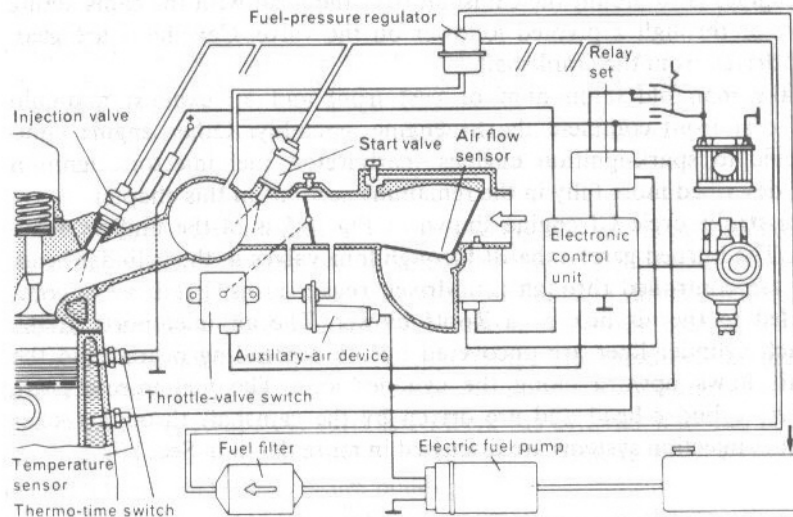


Figure 3.3. Schematic drawing of L-Jetronic port electronic fuel injection system (Source: Heywood 1998)

### 3.2. 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 engine's maximum allowable speed whereas the maximum torque is developed around or slightly above the half of maximum operating speed.

Engine torque is normally measured with a dynamometer. The engine is secured to a test bench where its output shaft is coupled to the dynamometer rotor. Figure 3.4. illustrates the operating principle of a dynamometer. The rotor is braked either by electromagnetic, hydraulic or mechanical friction. The energy supplied by the engine is converted to heat and therefore the dynamometer needs adequate cooling. The opposing torque exerted on the stator is measured by balancing weights, springs, pneumatic or electronic means.



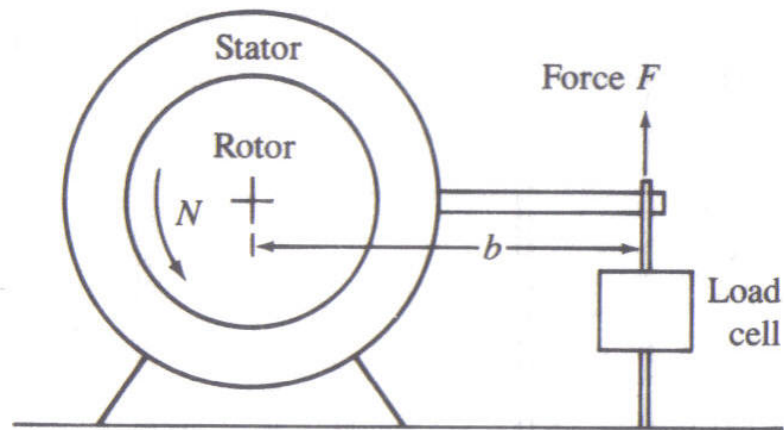


Figure 3.4. Schematic of a dynamometer

The load cell shown in Figure 3.4. reads the force  $F$  applied at a distance  $b$  from the center of the rotor. The *torque* applied by the engine on the dynamometer is  $T$ :

$$T \text{ (Nm)} = F \text{ (N)} \times b \text{ (m)} \quad (3.1)$$

Torque is the engine's ability to do work, whereas power is the rate of this work done. The power  $P$  delivered by the engine and absorbed by the dynamometer is the product of the torque and angular speed:

$$P = N \times T \quad (3.2a)$$

Using proper units Equation 3.2a becomes:

$$P \text{ (kW)} = 2\pi \omega \text{ (rev/s)} \times T \text{ (Nm)} \times 10^{-3} \quad (3.2b)$$

The value of engine power measured as described above is called *brake power*  $P_b$ . This is the usable power delivered by the engine to the load.

Another engine performance parameter is the *mean effective pressure*. Since both torque and power depend on engine size, dividing these values by the total volume swept by the cylinders of the engine, gives a more useful relative engine performance measure. The power used in the calculation is the brake power so the term is called *brake mean effective pressure*  $b_{mep}$ .

$$mep(kPa) = \frac{P_b(kW) \times n_r \times 10^3}{V_d(dm^3) \times \omega(rev/s)} \quad (3.3)$$

$n_r$  is the number of crank revolutions for one complete cycle, 2 for the four-stroke engines and 1 for the two-stroke engines;  $V_d$  the total displaced volume of the cylinders.

In engine tests, the fuel consumption is measured as a flow rate. Again the dependence of the flow rate on engine size makes the use of a parameter called *brake specific fuel consumption* necessary, the fuel flow rate per unit power output. It measures how efficiently an engine is using the fuel to do useful work.

$$bsfc(g/HP \cdot h) = \frac{\dot{m}_f(g/h)}{P_b(HP)} \quad (3.4)$$

As seen, the bsfc has units. A dimensionless parameter that relates the desired engine output (power) to the necessary input (fuel flow) would be of more fundamental value. The ratio of the work produced to the amount of heat energy that can be released in the combustion process is called *brake thermal efficiency*.

$$\eta_{bth} = \frac{P_b(kW)}{\dot{m}_f(kg/s) \times Q_{LHV}(kJ/kg)} \quad (3.5)$$

The fuel energy supplied that can be released by combustion is given by the mass of fuel supplied  $\dot{m}_f$  to the engine times the lower heating value  $Q_{LHV}$  of the fuel. The heating value of a fuel is determined in a standardized test procedure in which a known mass of fuel is fully burned with air, and the thermal energy released by the combustion process is absorbed by a calorimeter as the products cool down to their original temperature.

Practically, the energy supplied to the engine by the fuel is not fully released as thermal energy in the combustion process because the actual combustion is incomplete. When enough air is present in the cylinder to oxidize the fuel completely, almost all

(more than 96 percent, Heywood 1988) of this fuel energy supplied is transferred as thermal energy to the working fluid.

### **3.3. Combustion in Spark Ignition Engines**

In SI engines, combustion of the fuel-air mixture is initiated by a spark generated between the electrodes of a spark plug. The intake and compression strokes are designed to prepare the mixture for combustion by completely vaporizing the fuel and heating the mixture to just below its auto-ignition temperature. This is one reason, in addition to controlling emissions, for the current practice of limiting the maximum compression ratio of SI engines to about 10:1. Near the end of compression, the mixture is well conditioned for combustion and the spark is discharged to initiate the combustion process. For best fuel economy, the combustion process must be completed as close as possible to TDC. This requires that the spark timing be controlled for varying operating speed and load conditions of the engine. Fuel metering and control, according to the engine load requirements, and with minimum variation from cylinder to cylinder and cycle to cycle, is essential for good fuel economy, power output, and emission control of the engine. Both carburetors and fuel injection systems are used for fuel-metering control. Because of the superior control capabilities of fuel injection systems, they are nearly universally used today in production automotive applications. Carburetors are used for applications with less-stringent emission requirements, like small engines for lawn and garden equipment. Optimum fuel economy, coinciding with maximum thermal efficiency, is obtained at part throttle with a lean mixture as a result of the fact that the heat release from lean mixtures suffers minimal losses from dissociation and variation of specific heat effects when compared with stoichiometric and rich fuel-air ratios. Maximum power is obtained at full throttle with a slightly rich mixture, an indication of the full utilization of the air inside the cylinders. Idling, with a nearly closed throttle, requires a rich mixture because of the high percentage of exhaust gas residuals that remains in the cylinders. The fuel-air mixture requirement under transient operation, such as acceleration, requires a rich mixture to compensate for the reduced evaporation caused by the sudden opening of the throttle. Cold starting also requires a rich mixture to ensure the vaporization of sufficient amounts of the highly volatile components in the fuel to achieve proper ignition.

The combustion processes in SI engines can be divided into two categories, normal and abnormal. The normal combustion process occurs in three stages: initiation of combustion, flame propagation, and termination of combustion. Combustion normally starts across the spark plug gap when the spark is discharged. The fuel molecules in and around the spark discharge zone are ignited and a small amount of energy is released. The important criterion for the initial reaction to be self-sustaining is that the rate of heat release from the initial combustion be larger than the rate of heat transfer to the surroundings. The factors that play an important role in making the initial reaction self-sustaining, and thereby establishing a flame kernel, are the ignition energy level, the spark plug gap, the fuel-air ratio, the initial turbulence, and the condition of the spark plug electrodes. After a flame kernel is established, a thin spherical flame front advances from the spark plug region progressively into the unburned mixture zone. Flame propagation is supported and accelerated by two processes. First, the combined effect of the heat transfer from the high-temperature flame region and the bombardment by the active radicals from the flame front into the adjacent unburned zone raises the temperature and accelerates the rate of reactivity of the unburned mixture region directly adjacent to the flame front. This helps to condition and prepare this zone for combustion. Second, the increase in the temperature and pressure of the burned gases behind the flame front will cause it to expand and progressively create thermal compression of the remaining unburned mixture ahead of the flame front. It is expected that the flame speed will be low at the start of combustion, reach a maximum at about half the flame travel, and decrease near the end of combustion. Overall, the flame speed is strongly influenced by the degree of turbulence in the combustion chamber, the shape of the combustion chamber, the mixture strength, the type of fuel, and the engine speed. When the flame front approaches the walls of the combustion chamber, the high rate of heat transfer to the walls slows down the flame propagation and finally the combustion process terminates close to the walls because of surface quenching. This leaves a thin layer of unburned fuel close to the combustion chamber walls which shows up in the exhaust as unburned hydrocarbons.

Abnormal combustion may occur in SI engines associated with two combustion phenomena: knock and surface ignition. Knock occurs near the end of the combustion process if the end portion of the unburned mixture, which is being progressively subjected to thermal compression, autoignites prematurely before the flame front reaches it. As a result of the sudden energy release, a violent pressure wave propagates

back and forth across the combustion chamber, causing the walls or other parts of the engine to vibrate, producing a sharp metallic noise called knock. If knock persists for a period of time, the high rate of heat transfer caused by the traveling high pressure and temperature wave may overheat the spark plug electrode or ignite carbon deposits that may be present in the combustion chamber, causing uncontrolled combustion and preignition. As a result, loss of power and serious engine damage may occur. Knock is sensitive to factors that increase the temperature and pressure of the end portion of the unburned mixture, as well as to fuel composition and other time factors. Factors that increase the probability of knock include increasing the temperature of the mixture by increasing the charge intake temperature, increasing the compression ratio, or turbo/supercharging; increasing the density of the mixture by turbo/supercharging or increasing the load; advancing the spark timing; increasing the time of exposure of the end portion of the unburned mixture to auto-ignition conditions by increasing the length of flame travel or decreasing the engine speed and turbulence; and using low-octane fuel and/or maximum power fuel-air ratios. Engine design factors that affect knock in SI engines include the shape of the combustion chamber and the location of the spark plug and inlet and exhaust valves relative to the location of the end portion of the unburned mixture.

Surface ignition is the ignition of the unburned mixture by any source in the combustion chamber other than the normal spark. Such sources could include overheated exhaust valves or spark plug electrodes, glowing carbon deposits, or other hot spots. Surface ignition will create secondary flame fronts which cause high rates of pressure rise resulting in a low-pitched, thudding noise accompanied by engine roughness. Severe surface ignition, especially when it occurs before spark ignition, may cause serious structural and/or component damage to the engine.

### 3.3.1. Exhaust Emissions

The products of combustion from IC engines contain several constituents that are considered hazardous to human health, including carbon monoxide (CO), unburned hydrocarbons (HC), and oxides of nitrogen (NO<sub>x</sub>). The concentration of gaseous emissions in the engine exhaust gases are usually measured in parts per million (ppm) or percent (%) by volume. There are principal schemes present for the reduction of these pollutants.

Carbon monoxide CO is a colorless, odorless, and tasteless gas that is highly toxic to humans. Breathing air with a small volumetric concentration (0.3%) of CO in an enclosed space can cause death in a short period of time. CO results from the incomplete combustion of hydrocarbon fuels. One of the main sources of CO production in SI engines is the incomplete combustion of the rich fuel mixture that is present during idling and maximum power steady state conditions and during such transient conditions as cold starting, warm-up, and acceleration. Uneven fuel distribution, poor condition of the ignition system, very lean combustion, and slow CO reaction kinetics also contribute to increased CO production in SI engines.

When unburned hydrocarbons HC combine with NO<sub>x</sub> in the presence of sunlight, ozone and photochemical oxidants form that can adversely affect human health. Certain HC's are also considered to be carcinogenic. The principal cause of HC in SI engines is incomplete combustion of the fuel-air charge, resulting in part from flame quenching of the combustion process at the combustion chamber walls, and engine misfiring. Additional sources in four-stroke engines may include fuel mixture trapped in crevices of the top ring land of the piston and out gassed fuel during the expansion stroke that was absorbed into the lubricating oil film during intake. In two-stroke SI engines, the scavenging process often results in a portion of the fresh mixture exiting the exhaust port before it closes, resulting in large HC emissions. Engine variables that affect HC emissions include the fuel-air ratio, intake air temperature, and cooling water temperature.

Oxides of nitrogen; nitric oxide (NO) is formed from the combination of nitrogen and oxygen present in the intake air under the high-temperature conditions that result from the combustion process. As the gas temperature drops during the expansion stroke, the reaction is frozen, and levels of NO persist in the exhaust products far in

excess of the equilibrium level at the exhaust temperature. In the presence of additional oxygen in the air, some NO transforms to nitrogen dioxide ( $\text{NO}_2$ ), a toxic gas. The NO and  $\text{NO}_2$  combined are referred to as oxides of nitrogen or  $\text{NO}_x$ . The production of  $\text{NO}_x$  is in general aggravated by conditions that increase the peak combustion temperature. In SI engines the most important variables that affect  $\text{NO}_x$  production are the air/fuel ratio, spark timing, intake air temperature, and amount of residual combustion products remaining in the cylinder after exhaust.

Lean mixture combustion, which promotes good thermal efficiency, also results in low HC and CO production but causes high levels of  $\text{NO}_x$  emission. Increasing the fuel/air ratio to reduce  $\text{NO}_x$  results in increased CO and HC emissions. Approaches to reduce total emissions fall under two categories; the first concentrates on engine design and fuel modifications and the second involves treatment of exhaust gases after leaving the engine. In SI engines, the first approach focuses on addressing engine variables and design modifications which improve in-cylinder mixing and combustion in an effort to reduce CO and HC emissions. To reduce  $\text{NO}_x$ , attention is focused on factors that reduce peak combustion temperature and reduce the oxygen available in the flame front. Design and operating parameters that have been implemented or modified for decreased emissions include compression ratio reduction, increased coolant temperature, modification of the combustion chamber shape to minimize surface-to-volume ratio and increase turbulence, improvement of intake manifold design for better charge distribution, use of fuel injection instead of carburetors for better mixture control, use of exhaust gas recirculation to reduce  $\text{NO}_x$  by lowering combustion temperatures, positive crankcase ventilation to reduce HC, and increased aromatic content in gasoline.

In the second approach, several devices have been developed for after treatment of exhaust products. A thermal reactor may be used to oxidize HC and CO. These typically consist of a well-insulated volume placed close to the exhaust manifold, with internal baffles to increase the gas residence time and an air pump to supply fresh oxygen for the oxidation reactions. Thermal reactors are ineffective for  $\text{NO}_x$  reduction and thus have limited application. Catalytic converters utilize a catalyst, typically a noble metal such as platinum, rhodium, or palladium, deposited on a ceramic substrate to promote reactions at lower temperatures. Two types are in use, oxidation converters and reduction converters. Oxidation catalytic converters use the excess air available in lean mixtures (or supplied from an external air pump) to oxidize CO and HC emissions. Reduction catalytic converters operate with low levels of oxygen to cause reduction of

NO<sub>x</sub>. Sometimes, dual catalytic converters are employed to treat all three pollutants with a reducing converter, to reduce NO<sub>x</sub>, placed upstream of an oxidation converter for treating CO and HC. This arrangement requires that the engine be operated with a rich mixture which decreases fuel economy. Three-way catalytic converters are a recent development that permits treatment of NO<sub>x</sub>, CO, and HC in a single device, thus reducing size and weight of the exhaust system. Proper operation of a three-way catalyst requires very nearly stoichiometric combustion. If the combustion is too lean, NO<sub>x</sub> is not adequately reduced, and if it is too rich, HC and CO are not adequately oxidized. There is a narrow band for equivalence ratio from about 0.999 to 1.007 within which conversion efficiency is 80% or better for all three pollutants (Kummer, 1980). Maintaining engine operation within this narrow mixture band requires a closed-loop fuel-metering system that utilizes an oxygen sensor placed in the exhaust system to monitor excess oxygen and control the fuel injection to maintain near stoichiometric combustion.

### 3.3.2. Combustion Stoichiometry

To develop a relation between the composition of the reactants (fuel and air) of a combustible mixture and the composition of the products, it is necessary to meter the air inlet and fuel supply rate.

The ratio of the air mass flow rate  $\dot{m}_a$  to the fuel mass flow rate  $\dot{m}_f$  is called the air fuel/ratio (A/F).

$$\text{Air/fuel ratio (A/F)} = \frac{\dot{m}_a}{\dot{m}_f} \quad (3.6)$$

There is also the inverse of the above term, namely the fuel/air ratio (F/A).

$$\text{Fuel/air ratio (F/A)} = \frac{\dot{m}_f}{\dot{m}_a} \quad (3.7)$$

The normal operating range for a conventional SI engine using gasoline fuel is  $12 < \text{A/F} < 18$ .



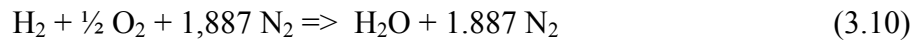
The relation between the composition of the reactants and the composition of the products depends only on the conservation of mass of each chemical element in the reactants, only the relative elemental composition of the fuel and the relative proportions of fuel and air are needed. If sufficient oxygen is available, a hydrocarbon fuel can be completely oxidized. The carbon in the fuel is then converted to carbon dioxide CO<sub>2</sub> and the hydrogen to water H<sub>2</sub>O. The general equation for the complete combustion of one mole of a hydrocarbon with air:



This is the equation for the stoichiometric (theoretical) proportions of fuel and air. That is, just enough air is present to oxidize all of the fuel. It is obvious that the stoichiometric air/fuel or fuel/air ratios depend on the chemical fuel composition. For gasoline (a reasonable approximation is C<sub>7.9</sub>H<sub>14.8</sub>) the equations becomes:



Whereas for hydrogen H<sub>2</sub> it is:



The molecular weights of oxygen, atmospheric nitrogen, atomic carbon, and atomic hydrogen are 32, 28.16, 12.001, and 1.008 respectively. Substituting these values and a simplification  $y = b/a$  in Equation 3.7 results in the expression:

$$(A/F)_s = (F/A)_s^{-1} = \frac{34.56(4+y)}{12.011+1.008y} \quad (3.11)$$

$$\text{Gasoline} = C_{7.9}H_{14.8} \quad (A/F)_s = 14.6$$

$$\text{Hydrogen} = H_2 \quad (A/F)_s = 34.3$$

Fuel-air mixtures with more than or less than the stoichiometric air requirement can be burned. With excess air or fuel-lean combustion, the extra air appears in the

products in unchanged form. With less than the stoichiometric air requirement, with fuel-rich combustion, there is insufficient oxygen to oxidize fully the fuel. The products are a mixture of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  with carbon monoxide  $\text{CO}$  and hydrogen as well as  $\text{N}_2$ . The product composition cannot be determined from an element balance alone and additional assumption about the chemical composition of the product species must be made. Since the composition of the combustion products is significantly different for fuel-lean and fuel-rich mixtures, and because the stoichiometric fuel/air ratio depends on the fuel composition, the ratio of the actual fuel/air ratio to the stoichiometric ratio (or its inverse) is a more informative parameter for defining mixture composition. The fuel/air equivalence ratio  $\phi$ :

$$\text{Fuel/Air equivalence ratio} \quad \phi = \frac{(F/A)_{\text{actual}}}{(F/A)_s} \quad (3.12)$$

The inverse of  $\phi$ , the relative air/fuel ratio  $\lambda$ ,

$$\text{Relative Air/Fuel ratio} \quad \phi^{-1} = \lambda = \frac{(A/F)_{\text{actual}}}{(A/F)_s} \quad (3.13)$$

For fuel-lean mixtures:  $\phi < 1, \lambda > 1$

For stoichiometric mixtures:  $\phi = \lambda = 1$

For fuel-rich mixtures:  $\phi > 1, \lambda < 1$

In practice, although with excess air condition, the composition of the products of combustion does not occur as in Equation 3.7. At normal combustion temperatures significant dissociation of  $\text{CO}_2$  and of  $\text{H}_2\text{O}$  occurs. Whether, at low temperatures, recombination brings the product composition to that indicated by these overall chemical equilibrium equations depends on the rate of cooling of the product gases.

## CHAPTER 4

### HYDROGEN AS AN ENGINE FUEL

There are a number of unique features associated with hydrogen that make it remarkably well suited in principle, to engine applications. Some of these most notable features are the following:

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 lean operational limit mixture in a spark ignition engine when fuelled with hydrogen is very much lower than those for other common fuels. This permits stable lean mixture operation and control in hydrogen fueled engines.

The operation on lean mixtures, in combination with the fast combustion energy release rates around top dead center associated with the very rapid burning of hydrogen–air mixtures results in high-output efficiency values. Of course, such lean mixture operation leads simultaneously to a lower power output for any engine size.

One of the most important features of hydrogen engine operation is that it is associated with less undesirable exhaust emissions than for operation on other fuels. As far as the contribution of the hydrogen fuel to emissions, there are no unburnt hydrocarbons, carbon monoxide, carbon dioxide, and oxides of sulfur, smoke or particulates. The contribution of the lubricating oil to such emissions in well-maintained engines tends to be rather negligible. Only oxides of nitrogen and water vapor are the main products of combustion emitted. Also, with lean operation the level of  $\text{NO}_x$  tends to be significantly smaller than those encountered with operation on other fuels.

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.

Varying the spark timing in hydrogen engine operation represents an unusually effective means for improving engine performance and avoidance of the incidence of knock. Also, the heat transfer characteristics of hydrogen combustion in engines are significantly different from those in engines operating on other fuels. The radiative component of heat transfer tends to be small yet the convective component can be higher especially for lean mixture operation.

The sensitivity of the oxidation reactions of hydrogen to catalytic action with proper control can be made to serve positively towards enhancing engine performance.

#### 4.1. Properties of Hydrogen

Hydrogen is an odorless, colorless gas. With molecular weight of 2.016, hydrogen is the lightest element. Its density is about 14 times less than air ( $0.08376 \text{ kg/m}^3$  at standard temperature and pressure). Hydrogen is liquid at temperatures below 20.3 K (at atmospheric pressure). Hydrogen has the highest energy content per unit mass of all fuels - higher heating value is 141.9 MJ/kg, almost three times higher than gasoline. Some important properties of hydrogen are compiled in Table 4.1.

Table 4.1. Physical properties of hydrogen, methane and gasoline

Property	Hydrogen	Methane	Gasoline
Density at 1 atm and 300 K ( $\text{kg} / \text{m}^3$ )	0.082	0.717	5.11
Stoichiometric Composition in air (% by volume)	29.53	9.48	1.65
Number of moles after combustion to before	0.85	1.00	1.058
LHV (MJ/kg)	119.7	46.72	44.79
Combustion energy per kg of stoichiometric mixture (MJ)	3.37	2.56	2.79

The specific physical characteristics of hydrogen are quite different from those common fuels. Some of those properties make hydrogen potentially less hazardous, while other hydrogen characteristics could theoretically make it more dangerous in certain situations. In Table 4.2. combustion characteristics are shown for certain fuels.

Table 4.2. Combustion properties of hydrogen, methane and gasoline

Property	Hydrogen	Methane	Gasoline
Flammability limits (% by volume)	4 – 75	5.3 – 15.0	1.2 – 6.0
Minimum ignition energy (mJ)	0.02	0.28	0.25
Laminar flame speed at NTP (m/s)	1.90	0.38	0.37 – 0.43
Autoignition temperature (K)	858	813	≈ 500 – 750

## 4.2. Hydrogen Safety Issues

Like any other fuel or energy carrier hydrogen poses risks if not properly handled or controlled. The risk of hydrogen, therefore, must be considered relative to the common fuels such as gasoline, propane or natural gas.

Since hydrogen has the smallest molecule it has a greater tendency to escape through small openings than other liquid or gaseous fuels. Based on properties of hydrogen such as density, viscosity and diffusion coefficient in air, the propensity of hydrogen to leak through holes or joints of low pressure fuel lines may be only 1.26 (laminar flow) to 2.8 (turbulent flow) times faster than a natural gas leak through the same hole (and not 3.8 times faster as frequently assumed based solely on diffusion coefficients). Since natural gas has over three times the energy density per unit volume the natural gas leak would result in more energy release than a hydrogen leak.

For very large leaks from high pressure storage tanks, the leak rate is limited by sonic velocity. Due to higher sonic velocity (1308 m/s) hydrogen would initially escape much faster than natural gas (sonic velocity of natural gas is 449 m/s). Again, since natural gas has more than three times the energy density than hydrogen, a natural gas leak will always contain more energy.

If a leak should occur for whatever reason, hydrogen will disperse much faster than any other fuel, thus reducing the hazard levels. Hydrogen is both more buoyant and more diffusive than either gasoline, propane or natural gas.

Hydrogen/air mixture can burn in relatively wide volume ratios, between 4% and 75% of hydrogen in air. Other fuels have much lower flammability ranges, natural gas 5.3-15%, propane 2.1-10%, and gasoline 1.2-6%. However, the range has a little

practical value. In many actual leak situations the key parameter that determines if a leak would ignite is the lower flammability limit, and hydrogen's lower flammability limit is 4 times higher than that of gasoline, 1.9 times higher than that of propane and slightly lower than that of natural gas.

Hydrogen has a very low ignition energy (0.02 mJ), about one order of magnitude lower than other fuels. The ignition energy is a function of fuel/air ratio, and for hydrogen it reaches minimum at about 25%-30% hydrogen content in air...

Hydrogen has a flame velocity 6 times faster than that of natural gas or gasoline. A hydrogen flame would therefore be more likely to progress to a detonation than other fuels. However, the likelihood of a detonation depends in a complex manner on the exact fuel/air ratio, the temperature and particularly the geometry of the confined space. Hydrogen detonation in the open atmosphere is highly unlikely.

The lower detonability fuel/air ratio for hydrogen is 13%-18%, which is two times higher than that of natural gas and 12 times higher than that of gasoline. Since the lower flammability limit is 4% an explosion is possible only under the most unusual scenarios, which is, hydrogen would first have to accumulate and reach 13% concentration in a closed space without ignition, and only then an ignition source would have to be triggered.

Should an explosion occur, hydrogen has the lowest explosive energy per unit stored energy in the fuel, and a given volume of hydrogen would have 22 times less explosive energy than the same volume filled with gasoline vapor.

Hydrogen flame is nearly invisible, which may be dangerous, because people in the vicinity of a hydrogen flame may not even know there is a fire. This may be remedied by adding some chemicals that will provide the necessary luminosity. The low emissivity of hydrogen flames means that nearby materials and people will be much less likely to ignite and/or hurt by radiant heat transfer. The fumes and soot from a gasoline fire pose a risk to anyone inhaling the smoke, while hydrogen fires produce only water vapor (unless secondary materials begin to burn).

Liquid hydrogen presents another set of safety issues, such as risk of cold burns, and the increased duration of leaked cryogenic fuel. A large spill of liquid hydrogen has some characteristics of a gasoline spill, however it will dissipate much faster. Another potential danger is a violent explosion of a boiling liquid expanding vapor in case of a pressure relief valve failure.

Hydrogen onboard a vehicle may pose a safety hazard. The hazards should be considered in situations when vehicle is inoperable, when vehicle is in normal operation and in collisions. Potential hazards are due to fire, explosion or toxicity. The latter can be ignored since neither hydrogen nor its fumes in case of fire are toxic. Hydrogen as a source of fire or explosion may come from the fuel storage, or from the fuel supply lines.

The largest amount of hydrogen at any given time is present in the tank. Several tank failure modes may be considered in both normal operation and collision, such as: catastrophic rupture, due to manufacturing defect in tank, a defect caused by abusive handling of the tank or stress fracture, puncture by a sharp object, external fire combined with failure of pressure relief device to open; massive leak, due to faulty pressure relief device tripping without cause or chemically induced fault in tank wall; puncture by a sharp object, operation of pressure relief device in a case of fire (which is the purpose of the device); slow leak due to stress cracks in tank liner, faulty pressure relief device, or faulty coupling from tank to the feed line, or impact-induced openings in fuel line connection.

Most of the above discussed failure modes may be either avoided or their occurrence and consequences minimized by: leak prevention through a proper system design, selection of adequate equipment, allowing for tolerance of shocks and vibrations, locating a pressure relief device vent, protecting the high pressure lines, installing a normally closed solenoid valve on each tank feed line; leak detection by either a leak detector or by adding an odorant to the hydrogen fuel (this may be a problem for fuel cells); ignition prevention, through automatically disconnecting battery bank, thus eliminating source of electrical sparks which are the cause of 85% gasoline fires after a collision, by designing the fuel supply lines so that they are physically separated from all electrical devices, batteries, motors and wires to the maximum extent possible, and by designing the system for both active and passive ventilation (such as an opening to allow the hydrogen to escape upward).

### 4.3. Features of Hydrogen for Engine Applications

In addition to the previous unique features associated almost exclusively with hydrogen, a number of others can be cited in support of hydrogen applications in engines. To list some of the main of these features:

Less cyclic variations are encountered with hydrogen than with other fuels, even for very lean mixture operation. This leads to a reduction in emissions, improved efficiency, and quieter and smoother operation.

Hydrogen can have a high effective octane number mainly because of its high burning rates and its slow preignition reactivity.

Hydrogen has been shown to be an excellent additive in relatively small concentrations, to some common fuels such as methane.

Its gaseous state permits excellent cold starting and engine operation. Hydrogen remains in gaseous state until it reaches its condensation point around 20 K.

Hydrogen engines are more appropriate for high-speed engine operation mainly due to the associated fast burning rates.

Less spark advance is usually needed, which contributes to better efficiencies and improved power output as the bulk of the heat release by combustion can be completed just after the TDC region.

Hydrogen engine operation can be associated with less heat loss than with other fuels.

Moderately high compression ratio operation is possible with lean mixtures of hydrogen in air, which permits higher efficiencies and increased power output.

Hydrogen engines are very suitable for cogeneration applications since the energy transfer due to condensing some water vapor can add up significantly to the thermal load output and the corresponding energy efficiency.

Hydrogen unlike most other commercial fuels is a pure fuel of well-known properties and characteristics, which permits continued and better optimization of engine performance.

The reaction rates of hydrogen are sensitive to the presence of a wide range of catalysts. This feature helps to improve its combustion and the treatment of its exhaust emissions.



The thermodynamic and heat transfer characteristics of hydrogen tend to produce high compression temperatures that contribute to improvements in engine efficiency and lean mixture operation.

Hydrogen high burning rates make the hydrogen fueled engine performance less sensitive to changes to the shape of the combustion chamber, level of turbulence and the intake charge swirling effect.

Internal combustion engines can burn hydrogen in a wider range of fuel-air mixtures than with gasoline. Hydrogen with wider flammability limits and higher flame speed makes it more efficient in stop and start driving.

Hydrogen can tolerate better the presence of diluents. This would allow a better exploitation of low heating value fuel mixtures.

Hydrogen can be employed quite effectively with oxygen-enriched air such as resulting from the electrolysis of water.

The gas is highly diffusive and buoyant which make fuel leaks disperse quickly, reducing explosion hazards associated with hydrogen engine operation.

#### **4.4. Limitations Associated with Hydrogen Engine Applications**

Much of the information reported in the open literature about the performance of engines on hydrogen as a fuel tends to highlight the positive features of hydrogen while de-emphasizing or even ignoring the many limitations associated with such fields of application. There is a need to focus equally well on these and suggest means for overcoming some of their negative aspects. Accordingly, the following is a listing of some features associated with hydrogen as an engine fuel that may be considered as requiring some remedial action:

Hydrogen as a compressed gas at 200 atmospheres and atmospheric temperature has merely around 5% of the energy of gasoline of the same volume. This is a major shortcoming particularly for transport applications.

Engines fueled with hydrogen suffer from reduced power output, due mainly to the very low heating value of hydrogen on volume basis and resorting to lean mixture operation.

The mass of the intake air is reduced for any engine size because of the relatively high stoichiometric hydrogen to air ratio.

There are serious potential operational problems associated with the uncontrolled preignition and backfiring into the intake manifold of hydrogen engines.

Hydrogen engines are prone to produce excessively high cylinder pressure and to the onset of knock. The equivalent octane number of hydrogen is rather low in comparison to common gasoline and methane.

The high burning rates of hydrogen produce high pressures and temperatures during combustion in engines when operating near stoichiometric mixtures. This may lead to high exhaust emissions of oxides of nitrogen.

There are serious limitations to the application of cold exhaust gas recirculation for exhaust emissions control.

Hydrogen engines may display some serious limitations to effective turbo charging.

There is always some potential for increased safety problems with hydrogen operation.

Hydrogen engine operation may be associated with increased noise and vibrations due mainly to the high rates of pressure rise resulting from fast burning.

Great care is needed to avoid materials compatibility problems with hydrogen applications in engines.

In certain applications, such as in very cold climates, the exhaust emission of steam can be an undesirable feature leading to poor visibility and increased icing problems.

The sensitivity of hydrogen–air mixtures to catalytic action can be occasionally considered undesirable as it may contribute to reduced safety and poorer control of the combustion process.

Hydrogen requires a very low ignition energy, which leads to uncontrolled preignition problems.

There is an increased potential for undesirable corrosion and lubricating oil contamination due to exhaust water vapor condensation.

There can be an increased potential for operational durability problems with lubricants.

Heat transfer losses can be high, yet under some conditions they can be quite low.

A hydrogen engine needs to be some 40–60% larger in size than for gasoline operation for the same power output. This could impose some reduction to engine

speed, increased mechanical and motoring losses and reduced tolerance to knocking. Also, some engine design modifications are needed.

#### **4.5. Improving the Operational Features of SI Hydrogen Engines**

A number of possible changes to the design and operational features of a hydrogen fueled S.I. engine can be suggested to affect the full potential of hydrogen in engine applications. These measures can include the following:

Employ lean mixtures with wide-open throttle. Means are to be provided to apply optimal variable partial throttling at extremely lean mixtures to effect better engine performance.

There is a need for uniquely optimized variations in the spark timing throughout so as to improve engine performance while avoiding knock.

The variation in spark timing with hydrogen is more effective in controlling the combustion process than with other fuels.

Optimum spark ignition characteristics in terms energy, spark plug gap size and material, plug geometry, electrical insulation etc. need to be employed.

Higher engine rotational speeds can be used to increase the power output of an engine operating on hydrogen while maintaining high efficiency and knock free operation.

It is preferable to have timed injection of the hydrogen whether within the manifold or directly into the cylinder, optimized for injection duration, timing and pressure. This is important especially for the avoidance of preignition and backfiring. Provision of some water injection when needed can be also made.

Higher compression ratios can be applied satisfactorily to increase the power output and efficiency, mainly because of the relatively fast burning characteristics of the very lean hydrogen–air mixtures.

Carefully controlled cooling of exhaust gas recirculation can be applied for knock avoidance and control. For lean mixture operation with hydrogen suitably heated exhaust gas recirculation can be used.

Direct hydrogen gas injection into the cylinder can be applied to produce suitably stratified mixtures for better performance and reduced exhaust emission.

In order to produce a power output comparable with that obtained with other fuels, larger size engines are needed. This will increase somewhat the frictional and motoring losses of the engine. Accordingly, a greater care is needed to reduce these losses so that to retain the high efficiency of hydrogen operation.

The volumetric efficiency needs to be maximized so as to enhance the power output.

Uniquely compatible and specially designed turbochargers need to be used for hydrogen engine applications.

There is a need to give a greater attention to heat transfer. Also, hotter water jacket temperatures than normally employed for gasoline operations are needed for lean operation. Cooler temperatures need to be employed, however, for high loads with hydrogen and to avoid uncontrolled preignition.

Resorts to catalytic methods to reduce exhaust  $\text{NO}_x$  emissions and any unconsumed hydrogen. Both of these components of the exhaust gas tend to be very low in concentration, especially for lean mixture operation. There are also excellent prospects to enhance the combustion process within the engine cylinder through the suitable provision of catalytic surfaces.

Further improvement in performance can be obtained by having the design features of the combustion chamber and its surfaces suitably optimized for hydrogen operation.

Variable valve timing needs to be incorporated and optimized to effect higher volumetric efficiency and better control of exhaust gas recirculation.

Hydrogen compatible lubricants and materials need to be ensured throughout. Appropriate safety precautions must be maintained under all possible operating conditions and scenarios.

When these measures are implemented in the design and operation of hydrogen fuelled spark ignition engines, then most of the apparent limitations associated with hydrogen as an engine fuel will be substantially minimized or disappear. Moreover, hydrogen engine operation can be shown to possess operational characteristics that are superior to those associated with other more conventional fuels.

## CHAPTER 5

### ENGINE MODIFICATIONS

SI engines are easily adaptable to gaseous fuels like propane, methane, and hydrogen. Slight modifications for the introduction of the fuel in appropriate amount are applied. A fuel supply system that can be tuned according to the engine's need is just good enough to make the engine work. In case of hydrogen there are certain additional issues concerning safety and backfire-safe operation throughout the whole operating region. The storage of the fuel is another aspect that affects the range of the vehicle operating on hydrogen. Due to its low energy per volume content, the compressed gas storage cannot compete with liquid gasoline.

Compared to gasoline, hydrogen's low energy per unit volume produces less energy in the cylinder. An engine running on hydrogen produces less power than with gasoline. Supercharging may help remedy this by compressing the incoming fuel/air mixture before it enters the cylinder. This increases the amount of energy per volume of fuel. Additional weight and complexity is added to the engine by such modifications. But the power gain and backfire resisting property (by cooling the cylinder with more air) compensates for the mentioned drawbacks.

Addition of spray nozzles for water is essential to provide backfire free operation. Although very simple in structure, it is important to supply the right amount of water according to load, engine speed and temperature.

If cryogenic hydrogen is to be supplied, material selection for the injectors, fuel supply line, tank and metering devices must be made accordingly. Since much progress has been made in the safe handling and storage of liquid hydrogen in space industry, the remaining focus needs to be done on applying this know-how to small vehicle systems.

## **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. Fuel Mixing**

Keeping the air and fuel separate until combustion is an important strategy for controlling the difficulties arising from the fast-burning properties of hydrogen. The low flammability limits and low energy required for ignition of hydrogen cause preignition and backfire when using hydrogen fuel. Ignition occurs when a fuel-air mixture ignites in the combustion chamber before the intake valve closes. Preignition can cause backfire when ignited fuel-air mixture explodes back into the intake system. It is most present at higher loads and at higher fuel-air mixtures near open throttle.

Preignition is not a necessary precursor to backfiring and probably not occurs under normal circumstances at moderate compression and equivalence ratios. Because of the low volumetric energy content of hydrogen, higher compression ratios or higher fuel delivery pressures are needed to avoid reduced power. Supercharging spark ignition engines compresses the fuel-air mixture before being inducted into the cylinder.

Direct fuel injection involves mixing the fuel with air inside the combustion chamber. The fuel and air are kept separate until then. If the fuel and air are mixed before entering the combustion chamber; the arrangement is called external mixing. A carburetor usually accomplishes this.

### **5.3. Mixture Formation and Engine Operation**

The extreme physical properties of hydrogen at ambient and cryogenic conditions are of beneficial influence on combustion as well as on mixture formation. In contrast to conventional fuels, the hydrogen fraction in a stoichiometric mixture at ambient temperature is about 30% of the mixture volume. The volumetric heat value of the hydrogen-air mixture (2890 J/l) results in a corresponding power loss at the engine compared to conventional fuel (3900 J/l). The wide flammability range of H<sub>2</sub>-air mixtures enables very lean operation with substantially reduced NO<sub>x</sub> emissions much more easily than with conventional fuels. Also, hydrogen offers a considerable reduction of air throttle and cylinder charge intake flow losses. In this point hydrogen differs considerably from other gaseous fuels such as natural gas or propane.

#### **5.3.1. Mixture Formation With Hydrogen At Ambient Conditions**

Substantial reduction of NO<sub>x</sub> emissions is demonstrated with lean mixture concepts without using catalysts at the exhaust. To achieve satisfactory engine operation several additional measures are necessary to prevent uncontrolled pre-ignition and backfiring into the intake manifold. Supercharging is an additional measure to compensate for the loss of power output, which is related to the lean mixture concepts. As a consequence of low energy content in the exhaust gas due to larger partial load efficiency and lower volumetric heat value, exhaust gas turbocharging is less suitable with hydrogen operation than with conventional fuel despite unthrottled air supply. Due to lower exhaust gas temperature with hydrogen operation (approximately 650 °C) under partial load, there is not enough energy available from the exhaust gas for charging up and improving torque. This “turbocharger hole” can be effectively bridged with an additional centrifugal compressor driven directly by the engine via a high speed transmission gear. Although the recognized turbocharger deficiency can be diminished through the reduction in flow orifice of the turbine’s case, this results in increased choking of the exhaust gas and in additional problems with uncontrolled pre-ignition. The problems with the hot residual gas could basically be reduced through an increase of the compression ratio (to 10:1 and 11:1). This measure, however, is contradictory to supercharging.

### 5.3.2. Internal Fuel Mixing

With internal fuel mixing air and fuel are mixed inside the combustion chamber. This is generally done as follows: air is taken in which also cools any hot spots in the cylinder, air intake valve is closed, fuel is injected, fuel inlet valve is closed, the mixture is ignited. When hydrogen is inducted into the cylinder under pressure no air is displaced in the combustion chamber. This prevents the power loss from externally mixed fuel-air systems. Theoretically, 20% more power is possible with directly injected hydrogen fuel than with the same engine using externally mixed gasoline. All types of engines can be modified in this way: four stroke, two stroke, diesel, and rotary. With internal mixing, high pressure is needed, up to 100 atm. A fuel pump is needed to supply fuel to the cylinder under pressure. Hydrogen is injected immediately after the intake valve closes and before the combustion chamber pressure reaches maximum.

The induction of air separately, rather than with the fuel, allows the air flow rate of a low density hydrogen engine to be essentially that of a carbureted engine operated on a higher density fuel such as gasoline.

Since liquid hydrogen is 10 to 20 times denser than gaseous hydrogen, direct injection of liquid hydrogen allows smaller and lighter valves. The relatively high density of liquid hydrogen, compared to gaseous hydrogen, causes it to generate pressure when evaporating. Because of this, internal fuel mixing combined with liquid hydrogen has the potential to surpass external mixing for gasoline or hydrocarbons.

There are two types of internal mixture formation: early injection and late injection. With early injection, fuel is introduced at the start of the compression stroke and continues until 90 degrees before TDC. With late injection, fuel is introduced at 5 degrees before TDC. High pressure is needed to get enough fuel into the chamber in a short time. With liquid hydrogen fuel, the fuel pump can supply some of this pressure. Fuel expansion from evaporating liquid hydrogen supplies the rest of the 100 atm pressure needed. Fuel injection in general, and late injection in particular, makes fuel-air mixing difficult because of the short time involved. Uneven mixtures cause: increased nitrous oxide formation, erratic ignition, ignition delay, incomplete combustion, delayed combustion.



These problems can be overcome by increasing the turbulence in the combustion chamber. This is accomplished in one of two ways. Changing the combustion chamber geometry or modifying the fuel injector arrangements.

### **5.3.3. External Fuel Mixing**

Without adequate cooling measures H<sub>2</sub>-air mixtures tend toward uncontrolled pre-ignition above an equivalence ratio  $\phi$  of about 0.7, by direct contact with the hot residual gas as well as hot spots in the combustion chamber where catalytic effects play a considerable role especially at low engine speed (Stewart 1986, Withalm G. and Gelse, W. 1986, Furuhashi 1989, Peschka 1986). Through appropriate cooling measures like, for example; modification of the cylinder head's cooling water routes for improved exhaust-side cooling of the combustion chamber, sodium- or lithium-filled outlet valves, as well as water injection into the combustion chamber via intake air, about 70% of the power of conventional fuel can be attained under steady operation with Otto-cycle engines. The torque is especially unsatisfactory at low engine speeds. Water injection, which can only realistically be used in test engines, can be replaced by equivalent exhaust gas recirculation due to its resulting suppression of uncontrolled pre-ignition. Although it has the advantage of improved mixture formation, it also results in an additional power and torque loss as a result of an increase in temperature and decrease in the oxygen fraction of the mixture.

When air and fuel are outside the combustion chamber the light hydrogen fuel displaces air mixture, thereby reducing power 20 to 30% compared to gasoline. Hydrogen fuel passes through a pressure regulator where it is reduced pressure for delivery to the fuel mixer.

Sequential single cylinder injection into the intake port with an open intake valve does not have any impact on the intake manifold concerning the mixture parameter because the hydrogen is added directly to the air flow at the cylinder intake thus avoiding mixture formation in the intake manifold to the greatest possible extent. Constant mixture composition, a vitally important prerequisite for good homogeneity of the cylinder charge, can be achieved only when the air mass flow rate during the intake phase remains constant as well as the hydrogen injection mass flow rate. An intake air

mass flow rate that varies periodically during the intake phase can result in local excessive fuel concentrations in the mixture that can lead to uncontrolled pre-ignition. For steady hydrogen operation with the external mixture formation, sequential single cylinder injection provides the best possible continuity of power and torque.

The use of electronic engine management improves variable power operation substantially. Considering that external mixture formation basically represents a simple procedure, in reality a very technically complicated concept has to be developed, although it is not clear whether substantial improvements can be achieved for two-valve engines.

#### **5.4. Water Induction**

Internal combustion engines waste about two-thirds of the combustion energy as heat. Adding water to hydrocarbon fuels allows the heat of combustion to combine the oxygen in the water with unburned carbon in the exhaust. This produces a combination of hydrogen and carbon monoxide. The hydrogen then burns, creating additional power.

The induction of water vapor into the cylinder reduces the combustion temperature of nitrous oxide formation. Water induction is an effective means of controlling nitrous oxide without loss of power, efficiency, or exhaust temperature. The effectiveness of water induction increases with rpm.

Some cylinders of the same engine may produce more nitrous oxide than others. With direct injection the equivalency ratio can be varied to each cylinder in response to individual emission characteristics. This is not possible with external mixing in carburetors where a uniform mixture is delivered to all cylinders. The non-uniformity of nitrous oxide formation from cylinder to cylinder requires a similar non-uniformity in water induction to compensate for this. Direct induction mixes water vapor with hydrogen before the introduction of air.

When the equivalency ratio exceeds 1.0 to 1.6 the possibility of preignition is greatly increased. This is because of the presence of hot residual gas or solid combustion residues such as oil ash. The cooling effect of water injection remedies this. As water induction reduces combustion temperature it also reduces the probability of preignition and backfire. By reducing the reaction rate of hydrogen and air in the

cylinder and increasing the energy needed for ignition, a larger range of mixtures may be used. Reducing the time, as well as the temperature, of combustion greatly reduces nitrous oxide emissions. This also serves to prolong engine life.

Higher engine rpm requires more water. The water flow rate must be adjusted to avoid water leaking past the piston rings. A standard gas tank, carburetor, and fuel pump may be adapted for water supply.

## CHAPTER 6

### EXPERIMENTAL SETUP

Tests were performed at the Engines Laboratory of the University of Dokuz Eylül, Izmir. 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 4<sup>th</sup> 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.

#### 6.1. Description of the Test Rig

Figure 6.1. illustrates the basic setup of the test bench. 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.

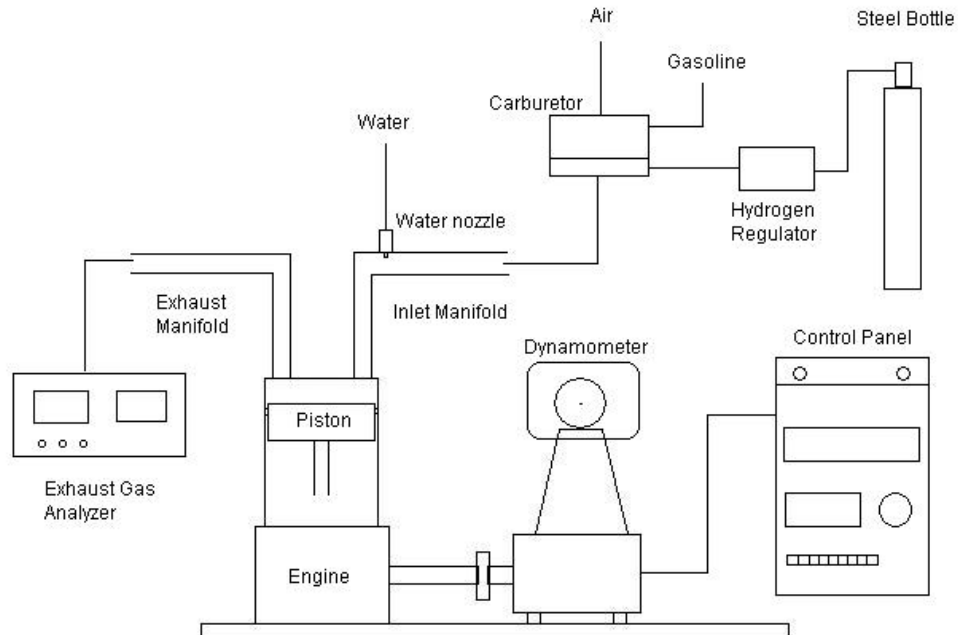


Figure 6.1. Block Diagram of Test Setup

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.

## 6.2. The Engine

The engine is a FIAT licensed 124 engine produced by TOFAŞ. The engine and subsystem specifications are:

Bore:	73.0 mm
Stroke:	71.5 mm
Valve:	8 valves (OHV)
Swept Volume:	1197 cc
Compression Ratio:	8.8:1
Power:	60 HP (DIN) at 5600 rpm
Torque:	89 Nm at 3400 rpm

Fuel Feeding:           Solex 2 barrel carburetor  
Ignition:                Distributor type, 10° static advance, no vacuum assistance  
Exhaust:                Standard muffler with final silencer muffler, no catalytic converter

Figure 6.2. gives an overview of the engine. There is an extra cooling fan installed for adequate cooling which is used throughout high load sessions.



Figure 6.2. General View of the Engine

### **6.3. Fuel Supply System**

Compressed hydrogen at 200 bar is used for fuelling the engine. 50 liter steel bottles were just enough for a load session. Pairs of bottles were always kept ready since during the tune up of the regulator considerable amount of hydrogen was spent.

An LPG conversion kit was used for hydrogen feeding. Since the experiments were made at partial load and the specified rated power for the regulator was 190 HP

(140 kW), it compensated for the high volumetric flow needs due to hydrogen's low density. Figure 6.3. shows the regulator installed above the radiator of the engine.

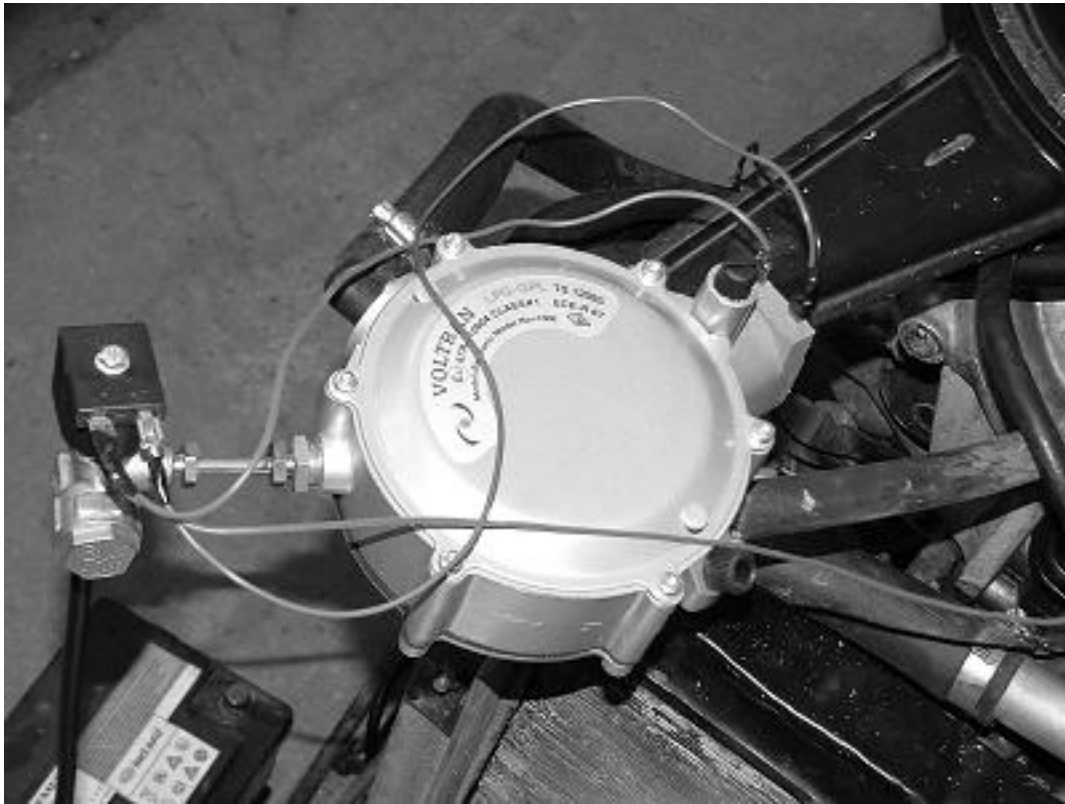


Figure 6.3. Second Stage Gas Regulator

This regulator drops the pressure of the supplied gas (from steel bottles) down to atmospheric pressure according to the engine's need. The supplied rate is varied according to the inlet manifold pressure which changes with the engine speed.

#### **6.4. The Dynamometer**

The test engine is loaded with the help of 80 HP loading capacity eddy current type dynamometer. The maximum allowable speed of the dynamometer is defined as 4000 rpm. A direct current flows through the coils of the stator creating a magnetic field within the cradled body. When the rotor rotates the field density varies and eddy currents are induced in the surface of the stator rings surrounding the rotor. The magnetic field lines of the eddy currents are directly opposed to the exciter field and

have a braking effect on the rotor. This braking effect is proportional to the excitation current.

The torque, which is thus applied to the cradled housing, is measured by the moment arm connected to the balance weights. A digital speed pick-up is used to measure the rotational speed. From these values the power of the test engine is calculated. This power is converted to heat and taken off by the cooling water which flows through the stator rings. In Figure 6.4. the stator housing and the mechanical gauge can be clearly seen.

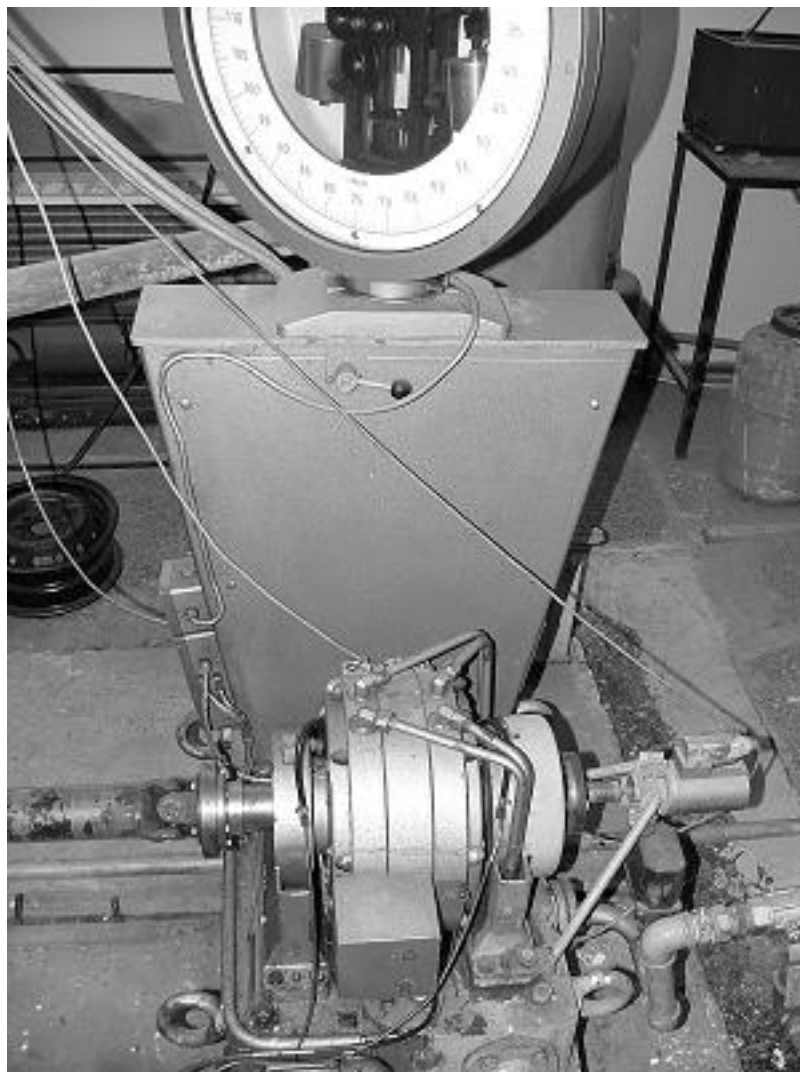


Figure 6.4. Eddy Current Dynamometer



The load is set by varying the excitation current of the stator coils. Constant load at any speed as well as variable load with speed can be adjusted as preferred, by two simple knobs on the control panel.

## 6.5. Exhaust Gas Analyzer

Two different devices have been used for reading the exhaust gas compositions of the set up. For standard emission readings, SUN MGA 1200 Exhaust Gas analyzer has been used. This analyzer is a compact unit that measures carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), and the hydrocarbon (HC) content in the exhaust emission of petrol driven engines by non-dispersive infra-red (NDIR) technology, and the O<sub>2</sub> content by a galvanic cell. A general view of the device is shown in Figure 6.5.



Figure 6.5. SUN Gas Analyzer

It also can measure engine rpm, oil temperature, Lambda ( $\lambda$ , air to fuel ratio) and corrected carbon monoxide (CO).

For nitrogen oxide (NO<sub>x</sub>) readings, MRU Vario D52 emission monitoring device was used. Electro-chemical sensors analyze O<sub>2</sub>, CO, NO, NO<sub>2</sub> and SO<sub>2</sub> continuously. CO<sub>2</sub> and HC measurements are possible with NDIR technology. Highly sensitive

NiCrNi thermocouples measure combustion air temperature and exhaust gas temperature separately. The exhaust gas is sucked by means of integrated automatic gas pump and supplied to the sensors. The analysis ensues automatically within seconds.

## CHAPTER 7

### RESULTS 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. At speeds below 2600 rpm serious backfire caused sudden loss of power and therefore the operating range for hydrogen was set between 2600 rpm and 3800 rpm (the upper limit is due to the rated speed of the dynamometer).

Sample calculation for power, thermal efficiency and mean effective pressure is as follows: For 3000 rpm,

Gasoline

$$T=22 \text{ Nm}$$

$$P \text{ (kW)} = 2\pi \omega \text{ (rev/s)} \times T \text{ (Nm)} \times 10^{-3}$$

$$P = 2\pi \times (3000 \times 1 / 60) \times 22 \times 10^{-3}$$

$$P = 6.9 \text{ kW}$$

Hydrogen

$$T = 19 \text{ Nm}$$

$$P \text{ (kW)} = 2\pi \omega \text{ (rev/s)} \times T \text{ (Nm)} \times 10^{-3}$$

$$P = 2\pi \times (3000 \times 1 / 60) \times 19 \times 10^{-3}$$

$$P = 6.0 \text{ kW}$$

Gasoline

$$P_b = 6.9 \text{ kW}$$

$$\eta_{bth} = \frac{P_b \text{ (kW)}}{m_f \text{ (kg/s)} \times Q_{LHV} \text{ (kJ/kg)}}$$

$$t = \text{time for 100 ml of fuel, } t = 74 \text{ s}$$

$$Q_{LHV} = 44000 \text{ kJ / kg}$$

$$\dot{m}_f = 760 \text{ kg/m}^3 \times 10^{-6} \text{ m}^3/\text{ml} \times 100 \text{ ml} / 74 \text{ s}$$

$$\dot{m}_f = 1.027 \times 10^{-3} \text{ kg / s}$$

$$\eta_{bth} = 15.3 \%$$

Hydrogen

$$P_b = 6.0 \text{ kW}$$

$$\eta_{bth} = \frac{P_b (kW)}{\dot{m}_f (kg / s) \times Q_{LHV} (kJ / kg)}$$

$$Q_{LHV} = 120000 \text{ kJ / kg}$$

$$\dot{m}_f = 0.084 \text{ kg/m}^3 \times 10^{-3} \text{ l/m}^3 \times 139 \text{ l/min} \times 1/60 \text{ min/s}$$

$$\dot{m}_f = 1.946 \times 10^{-4} \text{ kg / s}$$

$$\eta_{bth} = 25.5 \%$$

Gasoline

$$P_b = 6.9 \text{ kW}$$

$$V_d = 1.197 \text{ dm}^3, n_r = 2 \text{ (4-stroke engine)}$$

$$mep(kPa) = \frac{P_b (kW) \times n_r \times 10^3}{V_d (dm^3) \times \omega (rev / s)}$$

$$\omega = 3000 \text{ rev/min} \times 1/60 \text{ min/s}$$

$$\omega = 50 \text{ rev / s}$$

$$mep = 231 \text{ kPa}$$

Hydrogen

$$P_b = 6.0 \text{ kW}$$

$$V_d = 1.197 \text{ dm}^3, n_r = 2 \text{ (4-stroke engine)}$$

$$mep(kPa) = \frac{P_b (kW) \times n_r \times 10^3}{V_d (dm^3) \times \omega (rev / s)}$$

$$\omega = 3000 \text{ rev/min} \times 1/60 \text{ min/s}$$

$$\omega = 50 \text{ rev / s}$$

$$mep = 199 \text{ kPa}$$

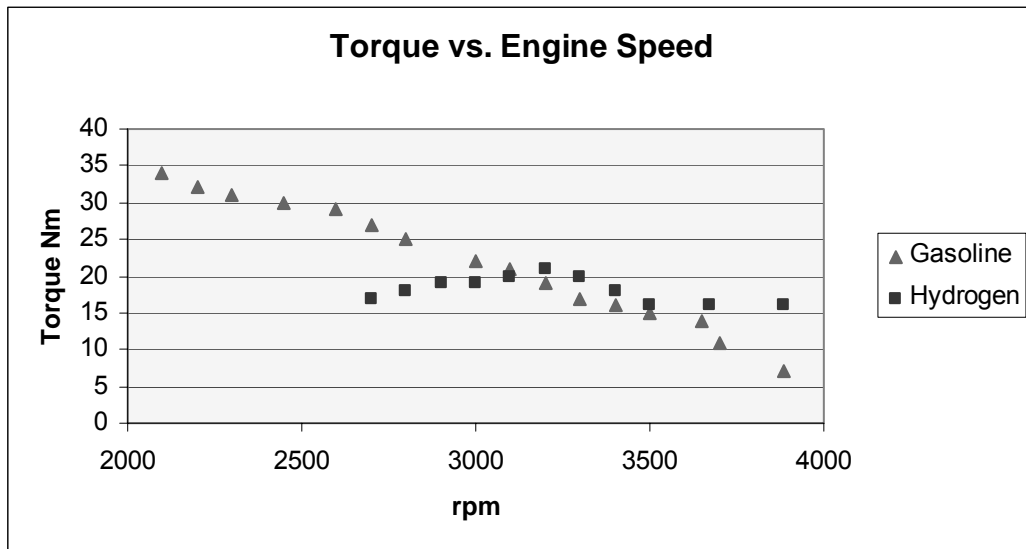


Figure 7.1. Torque comparison between gasoline and hydrogen

The variation of brake torque, which is read directly from the dynamometer, with engine speed can be clearly seen in Figure 7.1. At a speed of about 3100 rpm hydrogen achieves the torque values for gasoline and exceeds them at greater speeds. Since hydrogen has fast burning characteristics, it is expected to show better results at high speed operation. Figure 7.2. shows the brake power for both fuels. At low speeds hydrogen suffers power but competes well within the second operating speed range (3000 rpm – 4000 rpm).

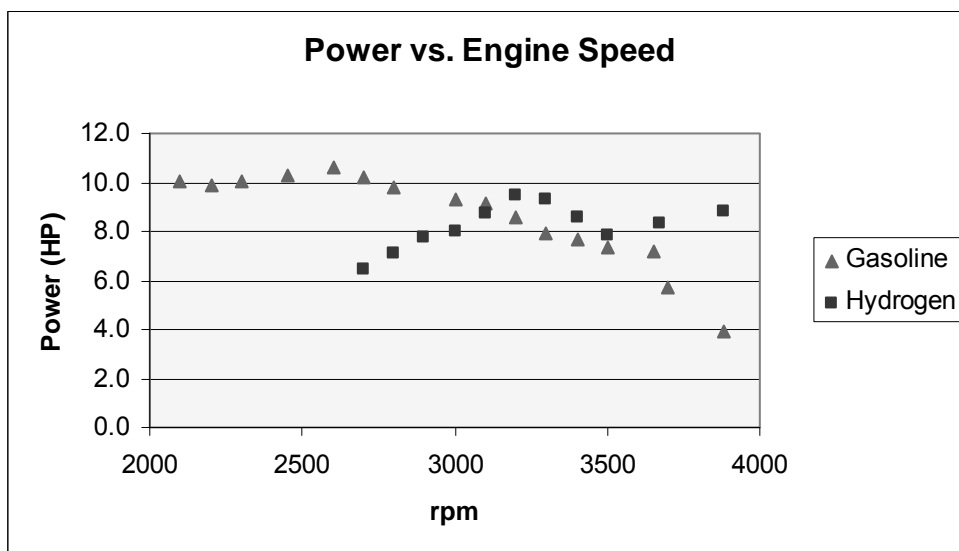


Figure 7.2. Power vs. engine speed

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.

Hydrogen has a wide flammability range (4-75 %). Certain non-homogeneity in the fuel air mixture has no considerable effect on its combustion. The mixture burns completely and thermal efficiency tends to be higher. With external mixture formation non-homogeneity is lower than internal mixture formation. This is also the reason for the high backfire tendency when external mixing is applied. There is fuel air mixture ready to burn flowing into the cylinder through the manifold. At any time this mixture can be ignited by a hot spot within the cylinder.

Comparison of brake thermal efficiency of gasoline and hydrogen operation is made in Figure 7.3. 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.

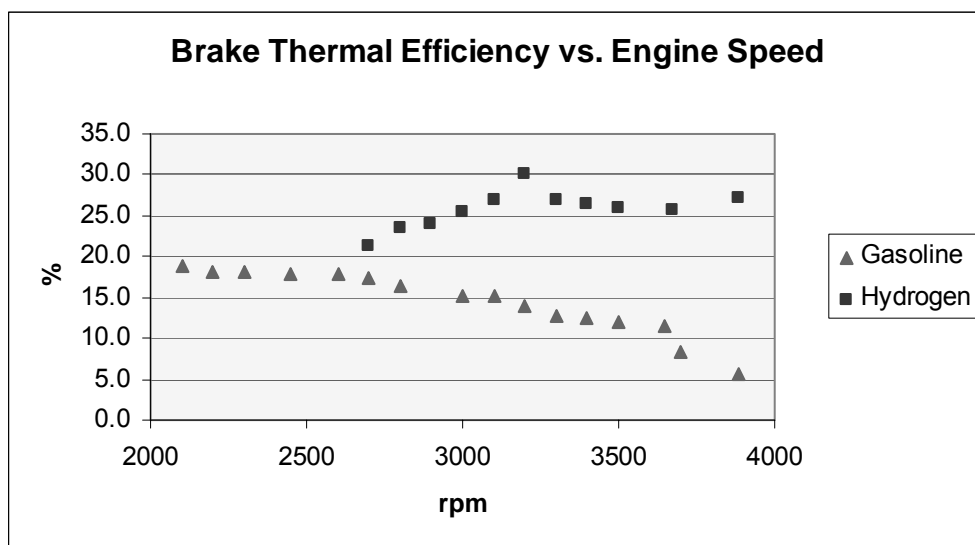


Figure 7.3. Brake thermal efficiency vs. engine speed

Plot of another performance parameter, the brake mean effective pressure is shown in Figure 7.4. Again at speeds below 3000 rpm the gasoline engine is more effective. Hydrogen operation shows a slightly better effectiveness at speeds above 3200 rpm.

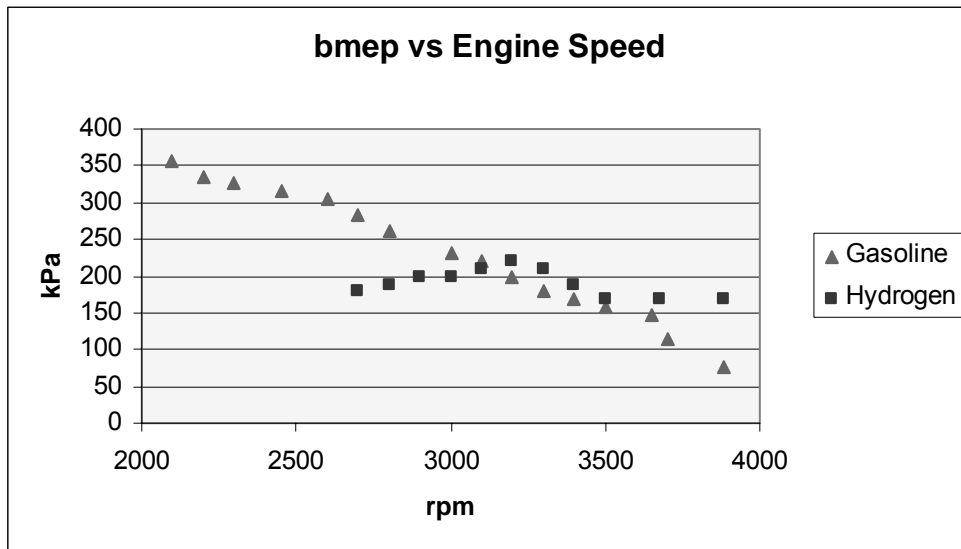


Figure 7.4. Brake mean effective pressure vs. engine speed

Temperature analysis of the exhaust gas can be made in Figure 7.5. 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.

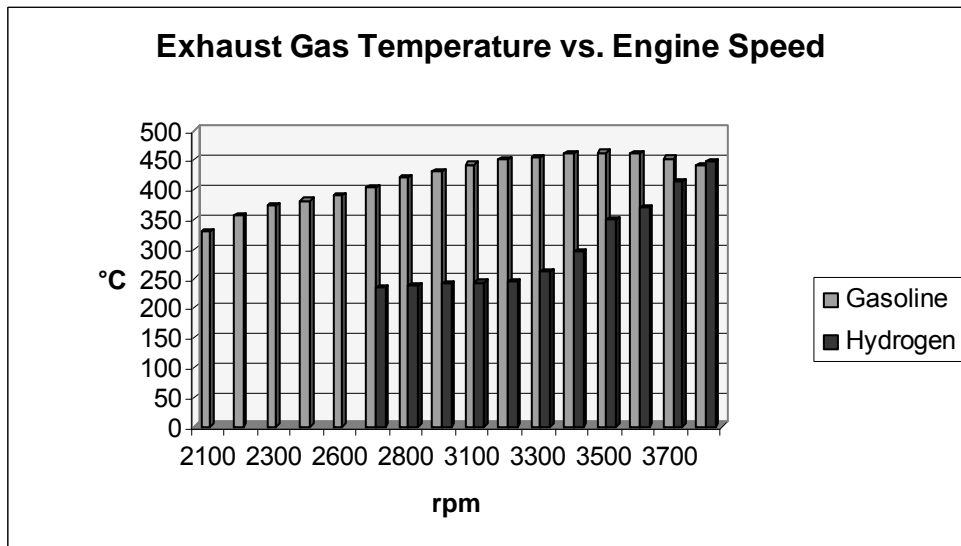


Figure 7.5. Exhaust gas temperature of gasoline and hydrogen engine

Figure 7.6. portrays the NO<sub>x</sub> levels of both engines in ppm. Significant decrease in NO<sub>x</sub> 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.

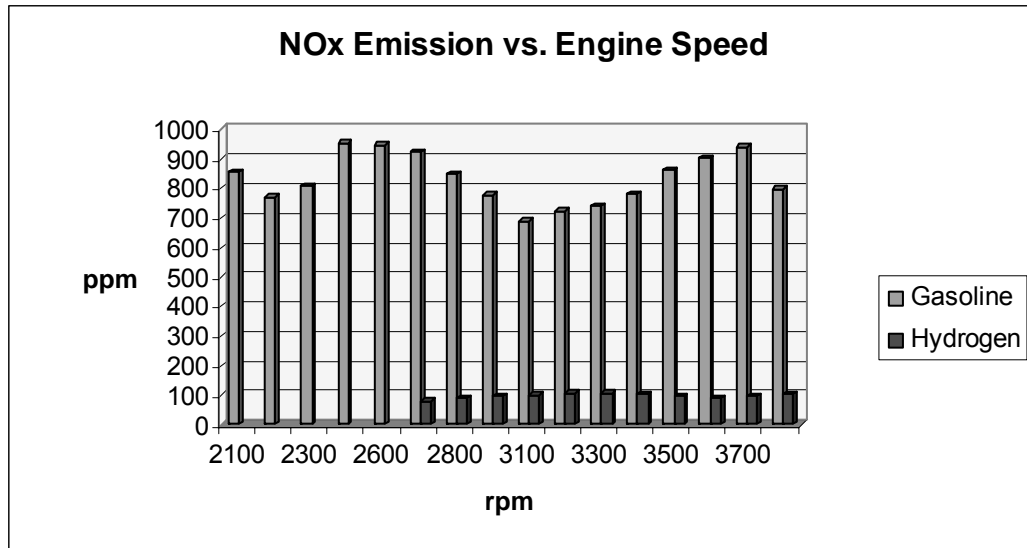


Figure 7.6. NO<sub>x</sub> levels vs. engine speed

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 7.7. 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. A similar presentation of results for carbon dioxide emissions is contained in Figure 7.8. 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 7.9., 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.

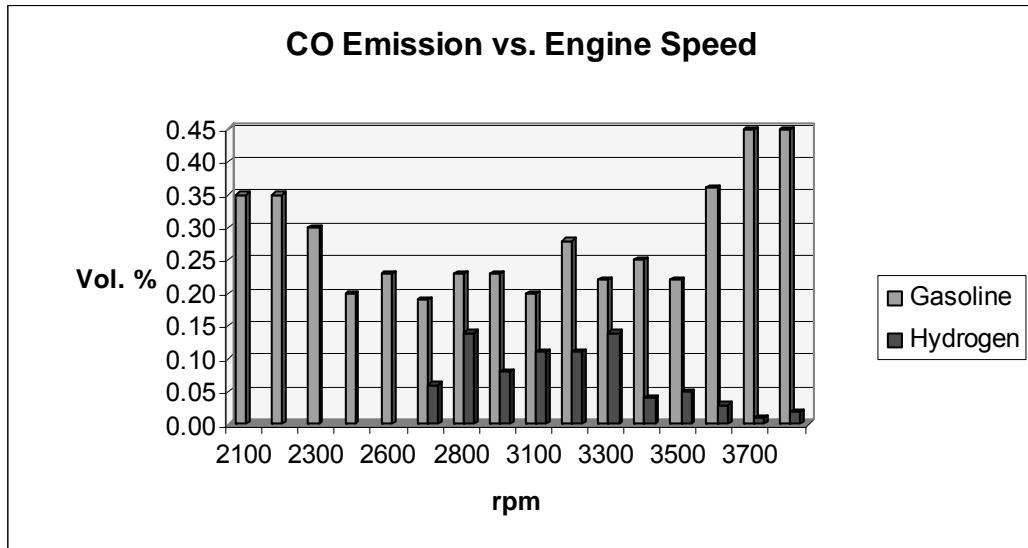


Figure 7.7. Carbon monoxide emissions

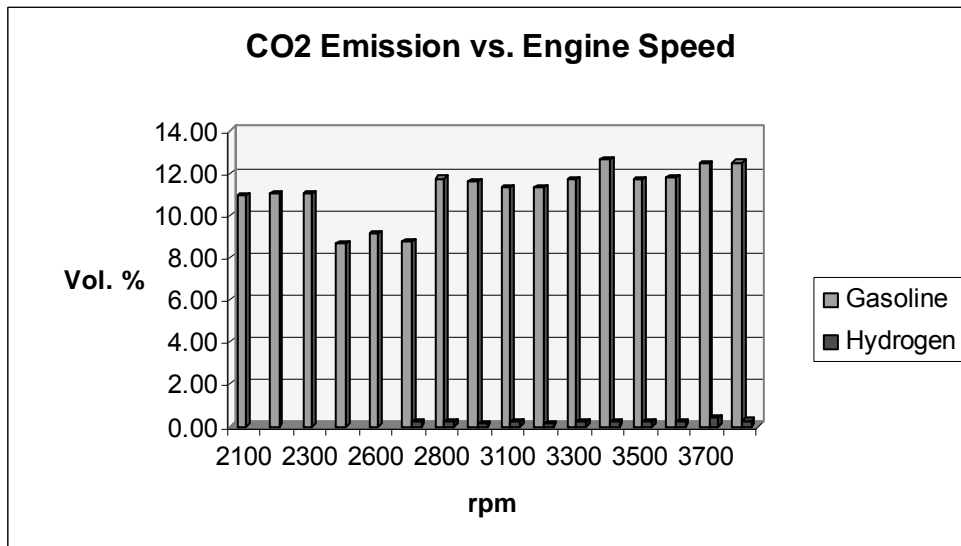


Figure 7.8. Carbon dioxide emissions

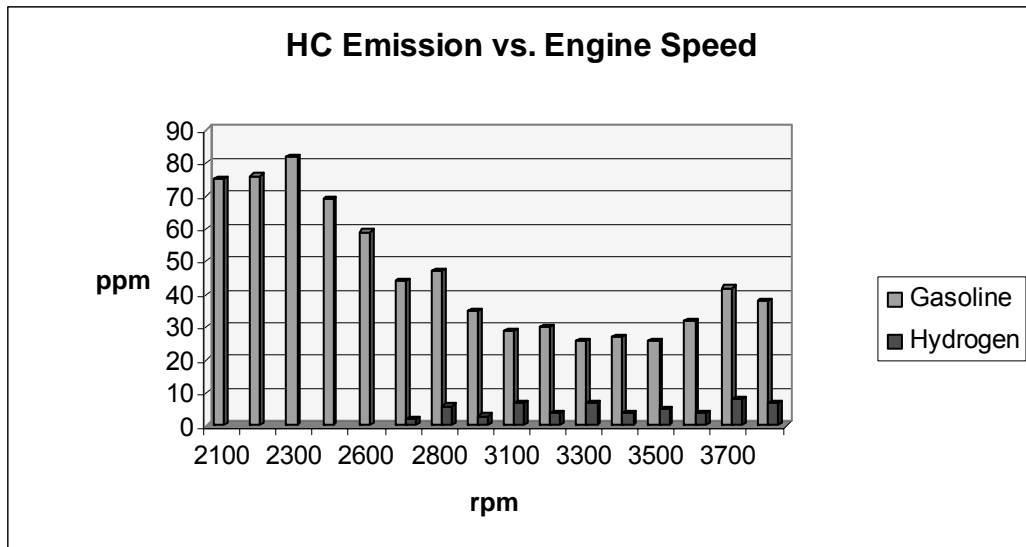


Figure 7.9. Hydrocarbon Emissions

Since the tests were performed at part load, fuel lean operation was needed. Especially to cool down the cylinder and operate the engine safely without backfire, in hydrogen operating case, mixture was leaned by following the oxygen content in the exhaust gas. Figure 7.10. shows the oxygen levels in the exhaust gas. During hydrogen operation, the engine was kept on extremely lean side.

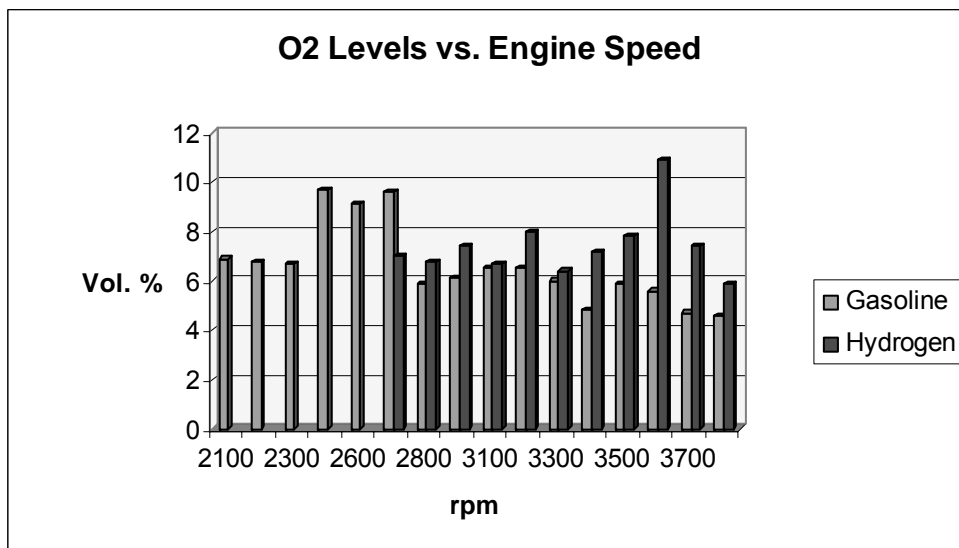


Figure 7.10. Oxygen Levels vs. engine speed

## CHAPTER 8

### CONCLUSION

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  $10^\circ$  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.

$\text{NO}_x$  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

- Veziroglu TN. 1987, International Journal of Hydrogen Energy 12:99 INSPEC Compendex.
- Winter CJ. 1987, International Journal of Hydrogen Energy 12:521 INSPEC Compendex.
- Serpone N, Lawless D, Terzian R. 1992, Solar Energy 49:221 INSPEC Compendex.
- Zweig RM. 1992, Proceedings of the Ninth World Hydrogen Energy Conference. Paris (France) :1995.
- Rever B. 2001, Renewable Energy World, Review Issue 2001–2002 ed. by James x James, vol.4, no 4, p177.
- Gretz J. 1992, Proceedings of the Second World Renewable Energy Congress. Reading (England) :2438.
- Block DL, Veziroglu TN. 1994, Hydrogen energy progress X, Proceedings of the Tenth World Hydrogen Energy Conference. Cocoa Beach (Florida, U.S.A.), Foreword.
- King RO, Rand M. 1955, “The hydrogen engine” Canadian Journal Technology 33:445–69.
- Erren RA, Campbell WH. 1933, “Hydrogen a Commercial fuel for internal combustion engines and other purposes” J Inst Fuel 1933; 6:277–90.
- Cox KE, Williamson KD. 1977, “Hydrogen: its technology and implications” Vols. I–V Boca Raton, FL: CRC Press.
- Peavey MA. 2003, “Fuel from Water: Energy Independence with Hydrogen”, (Merit Products) 11<sup>th</sup> Edition p. 135-137.

- Sierens R, Rosseel E. 1995. "Development of a multi-point timed injection S.I. natural gas engine" ASME Spring Engine Technology Conference, Marietta (Ohio). ICE, vol. 24, Natural Gas and Alternative Fuels for engines, p. 99–104.
- 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.
- Sierens R, Rosseel E. 1998 "Variable composition hydrogen-natural gas mixtures for increased engine efficiency and decreased emissions" ASME 1998 Spring Engine Technology Conference, Fort Lauderdale, Paper No 98-ICE-105, (26–29 April 1998).
- Furuhama S. 1995 "Problems of forecasting the future of advanced engines and engine characteristics of the hydrogen injection with LH<sub>2</sub> tank and pump" Calvin Rice lecture, ASME, (23 April 1995).
- Sorusbay C, Veziroglu TN. 1988 "Mixture formation techniques for hydrogen-fueled internal combustion engines" Proceedings of the Seventh World Hydrogen Energy Conference, Moscow, vol. 3, p. 1909–21.
- Kondo T, Hiruma M, Furuhama S. 1996 "A study on the mechanism of backfire in external mixture formation hydrogen engines" Proceedings of the 11th World Hydrogen Energy Conference, Stuttgart, vol. 2. (23–28 June 1996) p. 1547–56.
- Lee ST, Yi HS, Kim ES. 1995 "Combustion characteristics of intake port injection type hydrogen fueled engine" International Journal of Hydrogen Energy; 20:317–22.
- Guo LS, Lu HB, Li JD. 1999 "A hydrogen injection system with solenoid valves for a four-cylinder hydrogen-fueled engine" International Journal of Hydrogen Energy; 24:377–82.
- Peschka W. 1998 "Hydrogen: The Future Cryofuel in Internal Combustion Engines" International Journal of Hydrogen Energy, Vol. 23, No. 1, pp. 27-43.

- Heywood JB. 1998, *Internal Combustion Engine Fundamentals*, edited by A. Duffy, John M. Morris, (McGraw-Hill).
- Kummer, J.T. 1980, "Catalysts for automobile emission control" *Prog. Energy Combust. Sci.* 6:177-199.
- Stewart, W. F., 1986, "Hydrogen as a vehicular fuel" In *Recent Developments in Hydrogen Technology*, Vol.2, eds K. D. Williamson Jr. and F. J. Edeskuty. CRC Press, Cleveland, OH.
- Withalm, G. and Gelse, W., 1986, "The Mercedes Benz hydrogen engine for application in a fleet vehicle" In *Proceedings of 6<sup>th</sup> World Hydrogen Energy Conference*, Vol. 3, ed. N. Veziroglu, Pergamon, Oxford.
- Furuhama, S., 1989, "Hydrogen engine systems for land vehicles" *International Journal of Hydrogen Energy*, 14, 907.
- Peschka, W., 1986, "Liquid hydrogen – cryofuel in ground transportation" In *Advances in Cryogenic Engineering*, Vol. 31, Plenum Press, New York.