THE APPLICATION OF HYDROGEN TO AN AGRICULTURAL INTERNAL COMBUSTION ENGINE

by

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NOMENCLATURE

ϕ = Equivalence Ratio

η_t = Thermal Efficiency

r_v = Compression Ratio

k = Specific Heat

R.P.M. = Revolutions Per Minute

LP-gas = Liquid Petroleum Gas

°BTDC = Degrees Before Top Dead Center

°ABDC = Degrees After Bottom Dead Center

°BBDC = Degrees Before Bottom Dead Center

°ATDC = Degrees After Top Dead Center

INTRODUCTION

Recent experiences with oil embargoes and natural gas shortages have created an increasing concern with the future availability of energy. As a result of these happenings, many people realize that our fossil fuels are limited in supply and eventually new sources of energy will need to be developed. For the agricultural economy, the availability of sufficient quantities of fuel at the appropriate times is a necessity for maintaining high levels of food production. To replace agriculture's heavy reliance on natural gas and petroleum products, new, more reliable energy sources need to be developed.

Presently, the internal combustion engine represents the major instrument for converting chemical energy to mechanical energy on the farm. The pumping of irrigation water, powering of field operations, and transporting of produce to market all draw on the energy provided by the internal combustion engine. One possible source of chemical energy to replace hydrocarbon fuels in the internal combustion engine may be hydrogen.

Much work has been done in the field of hydrogen fueled engines. However, these studies have concentrated on its application to the automobile and other light duty vehicles. This thesis will focus on the application of hydrogen to powering heavier duty engines such as those used in irrigation and field operations. The ability of a hydrogen engine to meet the specialized requirements of these applications will be a major consideration in the selection of an engine performance test program.

LITERATURE SURVEY

The use of hydrogen in an internal combustion engine has mystified researchers as early as the 1820's. Reverend W. Cecil first proposed the use of hydrogen in an internal combustion device that harnessed the decrease in molar density resulting from the combustion of hydrogen and oxygen. Serious research into this topic began during the early part of the 20th century with the work of H. R. Ricardo, A. F. Burstall, and Rudolph Erren among others. All of these individuals confronted the problem of backfiring at fuel-air mixtures that approached stoichiometric conditions. Erren achieved control of this problem by injecting hydrogen into the cylinder during the compression stroke. However, this involved extensive modification and some complex auxiliary equipment (Billings and Lynch, 1973).

Work by R. O. King during the 1950's provided successful operation on hydrogen at high compression ratios without injection equipment (King, et al. 1958). Operation at a compression ratio of 20:1 was possible only at lean fuel-air mixture operations. However, the highest compression ratio at which maximum power could be attained was 14:1. King noted several possible causes of backfire as being hot spark plugs, exhaust valves, and oil accumulation in the cylinder. King speculated that the accumulation of oil may result in small high temperature particles in the residual gases which would ignite the incoming mixture (King, et al. 1948 and 1955). This hypothesis will be further discussed later in this thesis.

Energy and environmental interests have sparked a renewed interest in hydrogen combustion. Recent research efforts have involved three classes of engines: (1) automotive multi-cylinder engines, (2) small general utility engines, and (3) laboratory research engines. The general trend of research is to adapt hydrogen to automotive or other light duty internal combustion engines. Engine performance, exhaust emissions, and induction manifold backfire control have been the major areas of study.

The most extensive work with hydrogen engines has been performed by Billings Research Corporation (Escher, 1975). Feasibility demonstrations of the automotive applications of a hydrogen engine utilizing a wide variety of backfire control methods have been the major reported emphasis by this corporation. Besides more common backfire control methods such as water induction and exhaust gas recirculation, an increase in the combustion chambers surface area to volume ratio has been utilized (Lynch, 1975). A change of this nature will allow quicker cooling of the residual gasses which will hopefully eliminate backfire from hot particles in the residual gases. Only limited performance data has been released by this corporation. An 86% increase in efficiency of a Monte Carlo converted to hydrogen when compared to gasoline operation was reported by Billings for urban driving conditions.

A research team at UCLA has been heavily involved with the demonstration of hydrogen in automotive and laboratory test engines (Finegold, et al. 1973, Finegold and VanVorst, 1974). For one particular automotive test engine, brake thermal efficiency increases of 25 to 100% and 90% reductions in oxides of nitrogen emissions were reported for the engine operated on hydrogen (quality governed) as compared to gasoline operation. Finegold and VanVorst (1974) also noted that "Some form of charge dilution is essential to permit operation with hydrogen at high power output."

Without charge dilution, maximum horsepower attained with hydrogen was 40% less than attained on gasoline (Finegold and VanVorst, 1974).

A rather unique approach to quality governing of a hydrogen automotive engine has been demonstrated by Swain (1973) of the University of Miami. Hydrogen was fed to the cylinder separately from the air by a tube that opened into the intake valve seat. Thus, the intake valve controlled the separate openings for both the air and hydrogen. This separation of air and hydrogen was an attempt to reduce the chance of severe backfiring in the intake manifold. However, low-level backfiring continued to occur frequently if oil deposits were allowed to build up on the exhaust valve. Swain attributed the initiation of backfiring to preignition beginning at the sodium filled exhaust valve. Reported operation of this hydrogen engine never exceeded 50% of stoichiometric conditions. Efficiency of this system averaged about 50% greater than gasoline operation.

Variations of the hydrogen engine have also been experimented with by a number of institutions. General Moters Laboratory and the Jet Propulsion Laboratory of Pasadena, California are investigating hydrogen addition to gasoline in an attempt to improve fuel economy and reduce emissions (Escher, 1975). Perris Smogless Automobile Association is pursuing the development of a hydrogen-oxygen power system in order to completely eliminate harmful emissions (Underwood and Derges, 1971). A number of other institutions are also developing hydrogen power units. To avoid repetition, their findings will not be discussed.

One further area of work worth mentioning involved the application of hydrogen to compression ignition engines. Karim, Rashidi, and Taylor

(1974) of the University of Calgory in Canada have made extensive theoretical studies of the compression ignition characteristics of hydrogen-air mixtures inducted through the intake of a reciprocating engine. For this situation it is critical for the ignition delay period during the compression cycle to allow autoignition to occur at a time when the pressure rise will create peak performance. Karim noted that only a relatively narrow range of intake fuel-air mixtures and temperatures will allow acceptable timing of the pressure rise. He states that "acceptable operation with air appears possible only within a relatively narrow equivalence ratio range which is even more restrictive than with similar conditions involving spark induced flame propagation."

Compression ignition usually involves timing of the pressure rise by means of controlling the time the fuel is injected directly into the cylinder. Hydrogen injection has been used by several research groups recently. Compression ignition under these circumstances could not be achieved by a research group at Cornell University despite the use of compression ratios up to 29 to 1. Their conclusion was that "ignition lag time apparently is too long compared with the time available." R. G. Murray of Oklahoma State University has reported successful compression ignition with direct cylinder injection of hydrogen. However, no details have been released. Billings has reported compression ignition to be possible by mixed diesel/hydrogen injection but very little information is available (Escher, 1975). Karim and Klat (1976) have used hydrogen induction and diesel injection in a dual fuel engine to achieve satisfactory compression ignition operation. Their findings indicate that stable operation lies in a narrow range of diesel and hydrogen mixtures. The controlling factors are excessive pressure rises resulting in knock and erratic ignition. Presently available information indicates that compression ignition of hydrogen alone is impractical, but the use of a diesel pilot fuel with inducted hydrogen holds some potential.

The use of hydrogen injection also offers certain advantages in spark ignition engines. The primary purpose of hydrogen injection at Oklahoma State and Cornell is to prevent backfiring by timing injection to occur after the closing of the intake valve. This practice also eliminates the losses in volumetric efficiency and power experienced by a naturally aspirated hydrogen engine. Hydrogen's low volumetric energy density results in 29.6% of the cylinder volume being occupied by hydrogen at stoichiometric conditions when it is inducted through the intake manifold. Twenty to twenty-five percent less power can be expected from the same engine when operated on hydrogen in comparison to gasoline. Hydrogen injection will not only recover this loss of power, but can also have a supercharging effect. An increase in power of 10 to 20% above a gasoline baseline, can be expected with hydrogen injection (Escher, 1975).

There are certain problems to be expected with hydrogen injection. This practice requires relatively high-pressure hydrogen supply and sophisticated timing and flow control hardware. Relatively low thermal efficiencies have been reported with hydrogen injection engines due to the energy requirements of the injection process (Murray, et al. 1972). Space for location of an injector on many present spark ignition engines may also be a problem.

Much activity in the development of hydrogen power units has occured in recent times. Most of this work has studied the application of hydrogen to light duty automotive engines. Increases in efficiency have generally been noted. Backfiring and low volumetric energy densities have caused reductions in power levels achieved as compared to hydrocarbon fuels. A number of backfire control methods have been used in an effort to eliminate this problem. Hydrogen injection seems to hold some promise in eliminating backfire and power losses. However, compression ignition of hydrogen seems to be impractical.

INVESTIGATION

Objectives

The major objectives of this study are as follows:

1) Determine the applicability of hydrogen to an agricultural internal combustion engine.

2) Document the performance of an internal combustion engine while operating on hydrogen and LP-gas separately.

3) Examine the effectiveness of water induction for controlling backfiring.

4) Investigate the origin of backfiring in a hydrogen engine and other noteworthy combustion characteristics.

The primary purpose of this research is to determine the applicability of hydrogen to agricultural internal combustion engines. In particular, hydrogen use in a tractor or irrigation engine will be considered. For hydrogen to be accepted initially, presently used farm engines will need to be converted to hydrogen. The ease with which this can be accomplished will be of major importance. Consideration will be given on all modifications as to the services locally available to a farmer to make these modifications. Normally a machine shop or equipment dealer with some machine shop capabilities is available.

Major consideration will also be given to the performance of an engine operating on hydrogen. Specific requirements of an agricultural engine must be considered. Of course, for any farm engine available, power and fuel economy are important factors to consider. The reduction of power that can be expected in the conversion from a hydrocarbon fuel to hydrogen will also be a concern to the farmer. When considering the suitability of hydrogen to a tractor's power unit, the ability of the engine to react to momentary overloads is very important. Operation of an irrigation engine will be normally under constant speed and load conditions.

A third primary objective involves the application of water induction for controlling backfiring. This method of charge dilution seems to be the simplest potential method of promoting smooth engine operation with a minimum effect upon performance. The necessary rate of water induction to prevent backfiring and detrimental effects upon performance will be investigated.

Finally, an attempt will be made to determine cylinder pressure characteristics and temperatures at various critical points in the cylinder. Hopefully, this information will provide some insight into the cause of backfiring and other peculiar combustion traits of a hydrogen fueled engine. The effect of equivalance ratio and water injection on these parameters will be assessed.

Theory

The characteristics of hydrogen are quite distinctive from hydrocarbon fuels. Careful consideration of these characteristics is necessary before one can explain some of the peculiarities of a hydrogen engine performance. This section will include an explanation of these features of hydrogen and their effects upon engine power, efficiency, preignition, and backfiring.

Control of Backfiring

One of the first problems that most researchers encounter with hydrogen combustion in an internal combustion engine is backfiring. This nagging and possibly destructive phenomena restricts fuel-air mixtures to less than about ϕ=0.5. Control of this problem is necessary before one can achieve the maximum potential power from a hydrogen engine.

Three basic characteristics of hydrogen have been identified as contributors to the problem of backfiring (Table 1). The low ignition energy required to begin combustion of hydrogen-air mixtures makes it susceptible to small heat sources. Once combustion starts, it is very likely that it will continue due to the high flame speed and minimal quenching distance of hydrogen in air. Table 1 indicates that these properties vary greatly from common hydrocarbon fuels.

Several sources of sufficient thermal energy to initiate a backlashing have been indicated by past research. "Hot spots" in the combustion chamber, such as the spark plug electrode, exhaust valve, casting projections in the head, and carbon deposits in the cylinder may initiate preignition which could lead to backfiring. Elimination of these hot spots includes replacement of present engine components with

Table 1. Properties of Several Fuels*

	Hydrogen	Methane	Propane	Gasoline
Auto Ignition Temperature (°C)	585	540	510	440
Minimum Ignition Energy (mJ)	0.02	0.28	0.25	0.25
Maximum Flame Velocity Laminar (cm/sec)	270	38	40	30
Quenching Distance (cm)	0.06	0.22	0.19	----
Lower Heat of Combustion (Joules/gram)	119,900	50,020	46,360	44,200
Joules/cm^3 at 20°C and 76.00cm of Hg	10.05	33.35	84.98	----
Stoichiometric Mixture Volume % in Air	29.6	9.5	4	1.7
Flammability Limits Volume % in Air	4-75	5-15	2.2-9.5	1.3-7.1

*Most of this information is taken from VanVorst and Finegold.

sodium filled exhaust valves and cooler operating spark plugs. Also, removal of any casting projections or carbon deposits in the cylinder may be helpful. However, these efforts are often not sufficient for control of backfiring despite the fact that they are no longer a source of preignition except at high compression ratios and near stoichiometric conditions (King, 1955). It appears that backfiring is not always initiated by preignition.

The hypothesis promoted by King (1948) and later, Lynch (1975), explains that particulate matter in the exhaust gas may cause backfire. The higher heat capacity and greater mass of particulate matter causes this source to remain at higher temperatures longer than the surrounding residual gases. The thermal energy of these sources could ignite the fresh fuel-air mixture entering the cylinder. In an internal combustion engine, oil leakage by the valves and piston represents the most likely culprit. Carbon particles often remain unburned and suspended in the residual gases thus providing the particulate matter for initiating backfire. It has also been shown that inert particles as well as combustible carbon particles in the intake charge could induce backfire (King, 1948). Thus, backfire due to particulate matter in the residual gases seems highly possible.

If an explosion due to a heat source is to occur, the heat source and the chemical reaction around the heat source must release more energy than is conducted to the surroundings. The addition of an inert substance which increases the heat capacity of the mixture surrounding the heat source will tend to slow the thermal reaction. The mixture of fuel, air, and inert substance is able to absorb greater quantities of heat before and during a chemical reaction about a heat source, thus reducing the possibility of an uncontrolled explosion or backfire.

Water represents one such substance that should act in this manner to resist backfire caused by particulate matter in the residual gases and hot spots in the combustion chamber. In prior work with hydrocarbon fuels, reduced flame velocities and lower peak combustion temperatures were experienced with water mixed into the fuel-air charge (Nicholls, et al. 1969 and Quader, 1971). It was also noted that the reduction in combustion temperatures from evaporation cooling of the water was very minor compared to the charge dilution affect due to the increased heat capacity of steam. This indicates that water can enter the cylinder as steam or liquid with very little effect on its degree of backfire control. Thus, an inert substance such as water, which has the ability to slow the chemical reaction, offers a potential means of backfire control.

One final cause of backfire has been related to induced sparking (Billings, et al. 1974). Parallel or crossed ignition cables can experience induced sparks. Normally, in a gasoline engine this would not represent a problem. However, these induced sparks can cause difficulties due to the smaller ignition energy of hydrogen. Properly grounded and shielded cables can be effective in reducing the magnitude and frequency of the induced sparks and eliminating backfiring due to this cause.

Quality Governing

Another distinct characteristic of hydrogen is its wide flammability limits (Table 1). Because of this peculiarity, engine horsepower output can be controlled over a wide range by varying the richness of fuel-air mixture. The only potential area of difficulty is due to hydrogen's inability to burn lean enough to allow the engine to idle.

This concept is quite different from a conventional spark ignition engine which relies on variation in the charge density as a means of power control. A throttle plate in the air intake controls the density of the relatively constant fuel-air mixture that enters the cylinder. The throttle plate has the disadvantage of creating a vacuum in the intake system during part loads. The energy necessary to maintain the vacuum will need to be provided by the fuel. At part load, this loss of energy can have considerable effect upon the engine's thermal efficiency. However, at loads near the engine's maximum power, the inefficiency due to the throttle is much less. This last situation represents more closely an agricultural power unit in a tractor or on an irrigation well. The control of an agricultural engine burning hydrogen by varying fuel-air mixture may hold only limited advantage oyer a throttle controlled engine.

Performance

Some differences in a hydrogen engine's performance compared to operation on other common hydrocarbon fuels can be expected. As already mentioned, the fuel consumption efficiency can be improved by quality governing due to the elimination of the throttle. Examination of theoretical thermal efficiency of the Otto cycle reveals another major factor affecting the efficiency of hydrogen operation.

$$\eta_t = 1 - \frac{1}{r_v^{k-1}}$$

Thermal efficiency of the Otto cycle is dependent upon compression ratio, r_v, and the ratios of the specific heats, k, of the gases involved in the combustion process (Obert, 1973). For a specific engine with a fixed compression ratio, only the ratio of specific heat of the working fluid will influence the theoretical thermal efficiency. This factor is dependent upon the fuel, air, combustion gases produced during the expansion process, and the temperature of all of these fluids. As indicated by Figure 1, the ratio of specific heats for hydrogen and its products of combustion are higher than those of propane which should result in a higher efficiency for hydrogen combustion. Also, lean hydrogen operation should reduce the temperature of combustion and increase the ratio of specific heat of the products of combustion compared

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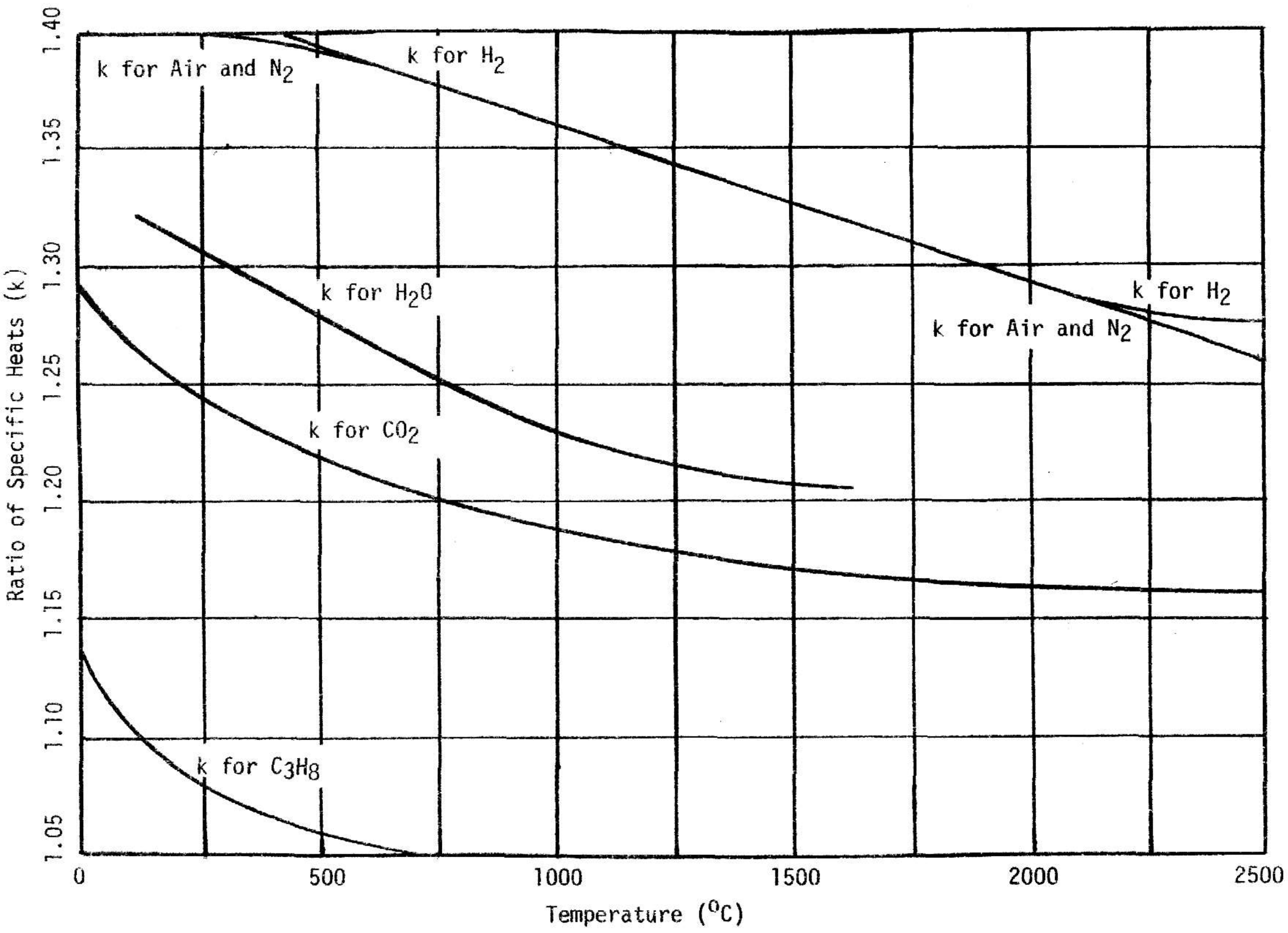

Figure 1: Specific Heats Ratio vs. Temperature

to stoichiometric operation of hydrocarbon fuels. Again, some increase in thermal efficiency should be expected.

Maximum power output of a naturally aspirated hydrogen engine should be less than a similar engine using hydrocarbon fuels. Hydrogen has a much lower volumetric energy density upon entering the cylinder than most other hydrocarbon fuels. As a result the volume of cylinder occupied by hydrogen at stoichiometric conditions is almost 30% of the total cylinder volume. By comparison, propane occupies only 4% of the cylinder.

The higher energy density of hydrocarbon fuels allows greater quantities of energy and oxygen necessary for releasing the energy to be present in the cylinder. The result is higher power output for hydrocarbon fuels such as LP-gas or gasoline. Finegold and VanVorst (1974) predicted that the power output of hydrogen should approach 75% of that obtainable with gasoline. A comparison of LP-gas and hydrogen based purely upon the heating value per volume of stoichiometric fuel-air mixture would lead one to expect hydrogen to achieve 88% of the power as achieved in the same engine on LP-gas. Of course, this does not consider the differences in factors affecting combustion pressure experienced during expansion which also affects maximum power levels.

Water induction into the intake manifold can have some major effects upon performance. Billings and Lynch (1973) found that rates of water induction up to five kilograms of water per kilogram of hydrogen were not detrimental to power or efficiency. Rates less than a five to one ratio have resulted in some increase in efficiency and power. However, performance deteriorated at rates greater than a five to one ratio. Water induction during operation on hydrocarbon fuels has produced similar results, but at different rates (Nicholls, et al. 1969).

An evaluation of the characteristics of hydrogen has provided several insights into its performance in an internal combustion engine. Ignition at inappropriate times may be a major problem due to the low ignition energy, high flame speed, and minimal quench distance of hydrogen. The addition of water should impede any chemical reaction in the intake mixture, thus reducing the possibility of untimely ignition. The performance and means of controlling hydrogen operation will also vary from conventional fuels due to a number of rather unique characteristics.