# PERFORMANCE AND EXHAUST EMISSION STUDIES OF A S. I. ENGINE USING HYDROGEN SUPPLEMENTED GASOLINE AND AMMONIA AS FUELS


*By*

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## CERTIFICATE

I, the undersigned, certify that the thesis entitled 'Performance and Exhaust Emission Studies of a S.I. Engine Using Hydrogen Supplemented Gasoline and Ammonia as Fuels', which is being submitted by Mr. B.B. Bansal in fulfilment of the requirements for the award of the degree of Doctor of Philosophy in the Faculty of Engineering of the Indian Institute of Technology, New Delhi is a record of the candidate's own bonafide research work carried out under my guidance. The matter embodied in this thesis has not been submitted in part or full, elsewhere for the award of any degree.

HBmathur 6.4.77

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# ABSTRACT

In the present time, virtually all light vehicles are powered by spark ignition engines using gasoline fuel- a petroleum product. There are limited reserves of these fuels and they are being depleted at a very fast rate because of their ever increasing demand. This has resulted in great scarcities and rapid rise in the price of gasoline. The situation is likely to be aggravated further as time passes. Moreover, the exhaust emissions from gasoline powered engines are fast becoming a major source of air pollution. In future, the cost of reducing these emissions may be prohibitive both energy wise and money wise.

Efforts are being made to conserve and stretch the available reserves of petroleum fuels as also to find 'clean' burning alternate synthetic fuels that may hopefully replace gasoline as spark ignition engine fuel in future. It is felt that some 'clean' burning synthetic fuels can be effectively used as supplementary fuel in the present day gasoline engines to stretch the available gasoline supplies and minimise exhaust emissions. These fuels may also come out to be potential future fuels which may completely replace gasoline for spark ignition engine applications.

Any consideration of synthetic fuels as viable solution to the above problems quickly leads to hydrogen as the most favoured choice. Two factors account for the mounting interest in hydrogen. First; the petroleum shortage provides a strong incentive to seek for non-petroleum based fuel which can be manufactured from abundantly available resources. Secondly, a hydrogen fueled engine promises a virtual elimination of exhaust hydrocarbon and carbon monoxide emissions and a controlled reduction in oxides of nitrogen by lean operation. It has been reported that conventional spark ignition engines can be modified for hydrogen operation. However, practical considerations such as handling, onboard storage, and safety etc. remain some of the challenges to the concept of total hydrogen operation.

Some of the advantages of total hydrogen operation can be gained by using hydrogen to supplement conventional fuel-gasoline. Present day spark ignition engines operate mostly on fuel rich mixtures. Fuel rich operation has the disadvantages of giving poor fuel economy, lower thermal efficiency and requiring exhaust gas aftertreatment. Lean combustion thus seems an obvious choice over rich combustion. Gasoline has a fairly narrow flammability range, and therefore, the extent of lean combustion is limited.

A solution to this dilemma can be reached by using a mixed fuel consisting of gasoline and a small amount of hydrogen. Hydrogen supplemented gasoline can burn leaner mixtures in the engine cylinder bringing about gasoline fuel economy. Moreover, it can permit use of higher compression ratios with subsequent improvement in thermal efficiency. Its use can also result in lower exhaust emission levels. The other advantage from the system that utilises mixtures of hydrogen and gasoline rather than hydrogen is that only smaller amount of hydrogen supply is required which minimises the handling and storage problems associated with the use of hydrogen.

In the first phase of the work reported here, gasoline supplemented with hydrogen has been used as spark ignition engine fuel. In order to evaluate the performance of such hydrogen supplemented gasoline, experimental investigations were carried out on a single cylinder variable compression Ricardo engine.

It has been observed that the lean limit of engine operation can be extended by increased hydrogen supplementation. The lean operating limit for gasoline was found to be 0.79 equivalence ratio. It could be extended to an equivalence ratio of 0.5 with a hydrogen fraction of 0.10 and to an equivalence ratio of 0.40 with a hydrogen fraction of 0.20. The lean operating limit for hydrogen has been found to be about 0.18 equivalence ratio.

Hydrogen supplementation has been found to permit higher compression operation of the engine without knock. Optimum compression ratios for various percentages of hydrogen supplementation have been determined. For different quantities of hydrogen supplementation, mixture strengths were varied over a wide range and spark timing was adjusted to give maximum power at each engine setting. Hydrogen fraction was varied from about 0.01 at the lowest overall air-fuel ratio to about 0.25 at the highest. Mixtures of gasoline with different hydrogen fractions were tested at different compression ratios in order to determine the optimum compression ratio for a particular hydrogen fraction and to determine the optimum hydrogen fraction for a particular compression ratio.

From the test results, various graphs have been plotted to evaluate the relative engine performance with hydrogen supplementation. The comparisons have been made on the basis of relative power output, specific fuel consumption and thermal efficiency.

The effect of lean operation with gasoline-hydrogen mixtures on engine emissions have also been studied. The concentrations of major exhaust pollutants, carbon monoxide, oxides of nitrogen, and unburned hydrocarbons were measured under various engine operating conditions with the help of suitable equipments. Non-dispersive Infrared Gas Analyser was used to measure oxides of nitrogen, carbon monoxide and hydrocarbons. Gas chromatograph fitted with flame ionisation detector was used to measure total hydrocarbons.

Hydrogen supplementation permits leaner operation of the engine with consequent reduction in the concentrations of oxides of nitrogen and carbon monoxide in the exhaust. Leaning the mixture to an equivalence ratio of 0.6 reduces exhaust $NO_x$ concentration to an exceedingly low figure. This reduction is achieved without loss of thermal efficiency but with a loss of power of about 40 per cent for the change of equivalence ratio from 1.0 to 0.6. Carbon monoxide concentrations in the engine exhaust also reduce to very low levels with the leaning of the mixture brought about by hydrogen supplementation.

Hydrocarbon emissions were found to increase at very lean mixtures. This increase in hydrocarbon emissions is because of increased quench layer thickness and reduced post flame oxidation of quenched hydrocarbons. At an equivalence ratio of 0.6 with optimum hydrogen supplementation hydrocarbon emissions were found to increase by about 100 per cent over the minimum level obtained with gasoline.

As already discussed, the problems of handling, storage and safety make it virtually impossible to use hydrogen as a complete fuel in spark ignition engines in the near future. Therefore, in order to utilise hydrogen as a substitute spark ignition engine fuel, the concept of storing hydrogen in some chemical carrier has been developed. Work on these hydrogen carriers falls into two major categories: intermetallic compounds (metallic hydrides) and liquid hydride fuels (ammonia and hydrazine). Technical feasibility of the use of metallic hydride fuel storage has been demonstrated by various investigators. However, mass and volume energy densities of most promising compounds are poor and the rare materials needed for their manufacture proclude any application in spark ignition engines in near future.

Ammonia is the most promising liquid hydride fuel. It appears to share the advantages of hydrogen (which result from its non-hydrocarbon composition) plus the additional advantage of non-cryogenic storage as a liquid.

In the second phase of the work reported here, ammonia has been used as a substitute S.I. engine fuel. It has been found that ammonia can be successfully used as a fuel for the present day S.I. engines, if it is introduced in a vapour form and a certain minimum amount of hydrogen is also supplied with it. Since ammonia needs higher ignition energy and has a low burning rate, the hydrogen supplied with ammonia acts as a catalyst for initiating ammonia combustion. Experiments were, therefore, performed using bottled hydrogen as a supplement to ammonia for successful operation.

A series of tests were conducted using hydrogen supplemented ammonia as fuel at various compression ratios, different engine speeds, optimum spark timings, and different hydrogen fractions.

It has been observed that the performance characteristics with ammonia are no different in nature from those obtained with gasoline. The experimental results confirm two theoretical expectations, (i) the power output is reduced with ammonia, and (ii) the peak power occurs at an equivalence ratio less than unity. Improvement in the performance can be brought about by using higher compression ratios. It was found that the peak power output with hydrogen supplemented ammonia increased by about 19 per cent when the compression ratio was raised from 7 to 10 and by 25 per cent when the compression ratio was raised from 7 to 12.

It has been observed that brake specific fuel consumption decreases with increase in compression ratio. A decrease of about 30 per cent in minimum specific fuel consumption was obtained when the compression ratio was raised from 7 to 12. Minimum specific fuel consumption occured at about 15-20 per cent lean mixtures.

Spark timing has been found to greatly affect the performance with hydrogen supplemented ammonia. It has been observed that hydrogen supplemented ammonia required larger spark advance as compared to gasoline. Experiments were, therefore, conducted to study the effect of spark timing on power output and specific fuel consumption.

It has been found that an optimum amount of hydrogen is needed to develop maximum power. It was observed that the power dropped sharpely if the hydrogen supplementation was less than the optimum. Experiments were performed to determine the optimum hydrogen supplementation at different compression ratios and engine speeds. Results have shown that the optimum hydrogen supplementation needed decreases as the compression ratio is increased. The optimum hydrogen supplementation requirement increased with increase in engine speed.

If the combustion of ammonia is considered, it becomes obvious that the exhaust of such engines will not contain carbon monoxide, carbon dioxide, and unburned hydrocarbons. The exhaust however, contains unburned ammonia in addition to the oxides of nitrogen.

Oxides of nitrogen in the exhaust were measured with the help of a Non-Dispersive Infrared Gas Analyser. These were measured at different equivalence ratios, hydrogen fractions, and compression ratios. It has been established that hydrogen supplemented ammonia fueled engine emitted little larger amounts of oxides of nitrogen in comparison to gasoline. Maximum oxides of nitrogen emission level increase with compression ratio. Hydrogen supplementation has a great effect on oxides of nitrogen emissions, which decrease remarkably at higher hydrogen fractions.

Measurements of the concentration of unburned ammonia in the exhaust were made using Nessler's technique in conjunction with a spectrophotometer. It was observed that the amount of unburned ammonia is greatly affected by hydrogen supplementation.

Apart from experimentally evaluating the engine performance and exhaust emissions with hydrogen supplemented gasoline and ammonia, certain analytical studies have also been carried out using suitable computer programs. Combustion calculations for determining equilibrium compositions for gasoline, ammonia and fuels containing various degrees of hydrogen supplementation, have been made with the help of these programs.

The above studies have clearly established that hydrogen supplemented gasoline and ammonia are two of the several options available to achieve gasoline conservation and meet the growing problems of fuel scarcity and environmental pollution due to automobile engine exhaust. Hydrogen supplemented gasoline can be used successfully in the present day spark ignition engines without engine modifications and can help in conserving and stretching the available petroleum reserves. Its use would improve the economy and performance of spark ignition engineswhile reducing the exhaust emissions to remarkably low levels.

Hydrogen supplemented ammonia can be employed in the present day spark ignition engines. With a considerable amount of research and development effort, future spark ignition engines can be suitably designed to obtain optimum performance while using ammonia as a complete fuel. The incentive for such effort is the promise of making potentially unlimited quantities of almost non-polluting fuels for future use in spark ignition engines.

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