HYDROGEN-FUELED SPARK IGNITION ENGINE—ITS PERFORMANCE AND EXHAUST EMISSION CHARACTERISTICS

By

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CERTIFICATE

I, the undersigned, certify that the thesis entitled, 'Hydrogen-Fueled Spark Ignition Engine - Its Performance and Exhaust Emission Characteristics' which is being submitted by Mr. P.R. Khajuria, 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 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.

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ABSTRACT

The economic and industrial growth of a nation is greatly dependent upon modern means of surface transport. This is all the more so for developing countries like India where the demand for automobiles and other light vehicles is growing rapidly with the pace of economic development and industrialization. These vehicles are powered by spark ignition engines which are quite reliable and efficient. In fact presently there is no other power-plant in sight for light vehicles which can compete with spark-ignition (S.I.) engine in cost, size, flexibility and reliability. It appears that at least for next few decades the S.I. engines will continue to have monopoly in the field of automobiles and other light vehicles.

The S.I. engine uses gasoline as fuel which was both plentiful and reasonably cheap in the world market upto 1973. The situation has since drastically changed and gasoline prices have increased manifold causing great scarcities and an unbearable strain on the economy of developing countries which have been depending on imports to meet their motor fuel requirements. Moreover, the resources of petroleum fuels are fast depleting, making the availability of gasoline supplies in future a matter of serious concern.

Apart from their irreplaceable nature, and growing scarcity another problem associated with the use of petroleum based fuels is the nature of their combustion products which cause environmental pollution. Gasoline powered vehicles are the main contributors to atmospheric carbon monoxide pollution in metropoliton cities. The hazardous effects of automobile exhaust pollution on human health, plant and animal life are well known.

These problems of fast dwindling resources of petroleum fuels and the hazard of environmental pollution caused by their combustion have focused the attention on the task of finding alternate 'clean' burning renewable fuels for use in automobiles. Broadly two types of alternative fuels have been under investigation for use in automobiles. These are : the two types of alcohols (ethanol, methanol) and hydrogen.

Alcohols are conveniently handled liquids and are already operational fuels. They can be obtained from renewable store of raw materials, organic matters including lignite, wood, coal, oil shale, natural gas and indirectly from municipal and farm wastes. However, their wide spread use in chemical industry makes it difficult to spare them for burning in automobiles on a large scale.

From many technical and economic considerations hydrogen seems to be the most suitable candidate fuel to substitute gasoline . Hydrogen can be manufactured from nuclear energy through electrolysis or thermal decomposition of water and it has been suggested as the most feasible future fuel.

Tasteless, Odourless and non-toxic by itself, hydrogen produces just clean energy and water vapours upon combustion with air, thus restoring quantitatively to the environment the water from which it is produced. Hence, there would never be a 'resource depletion' when hydrogen is burned as a fuel.

Hydrogen would be a particularly good fuel for spark ignition engines, because its wide flammability limit would permit high efficiency and unthrottled engine operation. Engine emissions of hydrocarbons, carbonmonoxide and carbon dioxide would be completely eliminated.

Hydrogen mixes easily with air and the mixture is quite stable at room temperature, however, the ignition energy of hydrogen is low compared to other gaseous and liquid fuels and it is ignitable at very low equivalence ratios. The flammability limits of hydrogen vary between 4 and 74 per cent by volume in air at room temperature and pressure. One of the consequences of this is the wide range of flame speeds and temperatures obtainable from hydrogen-air mixture.

S.I. engines using gasoline as fuel must be run very close to stoichiometric or richer mixtures thus producing conditions favourable to the formation of nitrogen oxides, unburned hydrocarbons and carbon monoxide in the exhaust. Hydrogen, on the other hand, may be burned so lean as to reduce peak temperatures to values at which dramatically less NO_x is produced and of course it is no source of hydrocarbons or carbon monoxide.

In addition to the favourable aspects of the properties of hydrogen noted above, its exceptionally high flame velocity leads to such rapid combustion that the 'instant-combustion' idealization of the Otto cycle is approached, which should lead to higher thermal efficiency. However, it could also cause rough running of the engine, and result in other associated combustion problems. These and other aspects of hydrogen utilisation as spark ignition engine fuels are matters of considerable current research interest.

In the work reported here, detailed analytical and experimental investigations of hydrogen as an S.I. engine fuel have been carried out. The analytical study involves application of a combustion model to predict combustion characteristics of hydrogen and a nitric oxide emission model to predict emission characteristics. The experimental investigations have been carried out using a single-cylinder, Varimax variable compression ratio engine modified to run on hydrogen. Both aspects of investigation have focused particular attention on the unthrottled pre-mixed hydrogen engine. Model calculations and experimental results are described and compared.

An engine combustion model has been formulated to determine the combustion rate with hydrogen fuel. Using this model the cylinder pressures and temperatures have been predicted and cylinder pressure crank angle traces have been compiled.

In the formulation of the combustion model the cylinder has been divided into two zones, one composed of burnt gases in chemical equilibrium and the other composed of unburned fuel air mixture along with residual gases. The flame front area has been found by assuming spherical propagation outward from the ignition point. By applying mass and energy balance equations, the temperature and pressure after each increment of flame advance have been determined for each zone. Temperature and composition dependent thermodynamic properties have been used and all processes except combustion have been assumed to be isentropic.

This combustion model has been employed to account for the hydrogen-air combustion process over a wide range of stoichiometry and spark advance for the Varimax engine operating at various speeds and compression ratios. Based on the computed results various graphs have been plotted showing the variation of combustion crank angle and flame speed with fuel air equivalence ratio, engine speed, compression ratio, etc. In addition pressure-time traces for various fuel-air equivalence ratios and compression ratios have been prepared. Plots for peak pressure and temperature variations across the cylinder for various equivalence ratios have also been obtained.

Although a spark ignition engine fueled with hydrogen would be free from carbon monoxide and hydrocarbon emissions, nitric oxide (NO)would still be a potential exhaust pollutant requiring control. In order to estimate the exhaust nitric oxide concentration an analytical model has been evolved. This is based on the experimental observations of Zeldovich and his co-workers, that the NO formation rate is much slower than the combustion rate and that most of the NO formation is after the completion of combustion. Using the 'frozen' expansion concept, the exhaust nitric oxide concentration has been computed by integrating the chemical rate equation. The burnt gases have been assumed to remain unmixed and they have been divided into a series of discret adiabatic zones of equal pressure but different temperature. The nitric oxide production has been computed for each zone during the entire expansion stroke till the opening of the exhaust valve. At this point the exhaust NO concentration has been arrived at by summing the contribution from all zones. On the basis of this model exhaust nitric oxide emissions for hydrogen fueled spark ignition varimax engine have been calculated for a wide variety of engine operating conditions, and variations of exhaust NO_x emissions with equivalence ratio at various speeds have been plotted.

In order to check on the analytical results and to know how to adapt spark ignition engines for operation of hydrogen fuel detailed experimental investigations have been carried out using Varimax research engine. The engine performance data over its entire operating range of speeds and loads has been collected at different compression ratios, spark timings, etc. using hydrogen as fuels. Various graphs showing the nature of engine performance characteristics with hydrogen fuel have been plotted.

Experimental plots of thermal efficiency variation with equivalence ratio at different engine speeds and compression ratios show that use of hydrogen as fuel can result in significantly higher cycle efficiencies. Hydrogen's extremely broad lean flammability limit enables power output regulation by mixture control rather than by throttling. Graphs showing the variation of mean effective pressure with equivalence ratio and specific fuel consumption have been plotted for different engine speeds and compression ratios. They indicate the feasible range of engine speeds and compression ratios for best results with hydrogen operation of the engine.

In order to assess the NO/NO_x emission characteristics of the engine extensive experiments have been carried out using a chemiluminescent NO/NO_x analyser. The experimental results have been plotted showing variation of exhaust NO/NO_x with equivalence ratio and compression ratio. It has been found that NO emission is maximum at an equivalence ratio of around 0.8 and it is extremely low for very lean mixtures.

NO formation process depends upon the available oxygen and the prevailing temperatures, and they occur in post flame gases. The type of fuel used effects the flame temperatures and through the stoichiometry the available oxygen. For equivalence ratios lower than 0.8 the NO formation is controlled by quenching of formation reactions during the expansion stroke, while for richer mixtures NO concentrations are primarily determined by the quenching of decomposition reactions during the expansion process. The experimentally determined trends of NO/NO_x emissions are in good agreement with the theoretically predicted results.

On the basis of the work reported here, it can be safely concluded that hydrogen-fueled S.I. engine is a feasible proposition. Such an engine having quality governing can operate with very lean mixtures giving much higher efficiency as compared to gasoline engine. It would have the additional advantage of emitting a cleaner exhaust free from hazardous carbon containing pollutants and as much as about ninety per cent lower exhaust NO emissions.

At higher outputs and higher equivalence ratios, charge dilution is one of the measures to ensure smoother operations. Narrower spark plug gap would have to be employed to account for hydrogen's 'low quench' distance and low ignition energy. These coupled with deposit free combustion chamber could ensure smoother operation without the problem of flashback past the intake valve and preignition during compression.

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