FUEL INDUCTION TECHNIQUES FOR A HYDROGEN OPERATED ENGINE

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Abstract—It is practically impossible to replace the internal combustion engines which have already become an indispensable and integral part of our present day life style, particularly in the transportation and agricultural sectors. Unfortunately, the survival of these engines has, of late, been threatened by the dual problems of the fuel crisis and environmental pollution. Therefore, to sustain the present growth rate of civilization, a non-depletable, clean fuel must be expeditiously sought. Hydrogen exactly caters to these specified needs. Hydrogen, even though "renewable" and "clean-burning" it does give rise to some undesirable combustion problems in an engine operation, such as backfire, pre-ignition, knocking and rapid rate of pressure rise. It has been experimentally evaluated that the fuel induction technique (FIT) does play a very dominant role in obtaining smooth engine operation. This paper discusses such various possible modes. Research work carried out by different investigators has been highlighted.

1. INTRODUCTION

A fuel has an infinite supply potential. It can be generated from water using any non-fossil energy source and upon combustion it produces water which goes back to the earth's water supply system from where it came. From an environmental standpoint, it is exceptionally clean.

The above-mentioned characteristics define a very desirable fuel and hydrogen does possess these characteristics. So situations arising out of the present-day energy crisis do not affect the hydrogen-fuel-system. As far as engine operation is concerned, a total hydrogen-fuelled engine will not emit unburnt hydrocarbons, CO, particulate matter, sulphur dioxide, smoke etc. From several practical considerations hydrogen is safer compared to conventional petroleum fuels. Being very light, leaking hydrogen rises up very rapidly through the air, thus creating an explosion possibility only to the space immediately above the leak. On the other hand, spilled gasoline creates safety-related problems which do persist for a long time. Because of low emissivity characteristics, radiation hazards from a hydrogen flame are of lesser consequence as compared to a gasoline flame.

It is evident that petroleum fuels are liquid at room temperature whereas hydrogen remains a gas even at a much lower temperature (i.e. — 253°C). The flammability limits, ranges of equivalence ratios over which the engine system is operable, auto-ignition temperature and minimum ignition energy are some of the properties which determine the suitability of the fuel for engine application. However, since some combustion characteristics of hydrogen fuel set it completely apart from other conventional fuels, unless these properties are appropriately exploited to an advantage for improved engine characteristics, they might give rise to various unwanted combustion problems.

2. UNDESIRABLE COMBUSTION PROBLEMS

Figure 1 shows the ranges of equivalence ratios suitable for hydrogen engine operation. A close look at the properties of the fuel brings in some very important points with respect to engine operation. Interestingly, most properties of hydrogen fuel if appropriately exploited to a point of advantage, could prove extremely desirable. On the other hand, the same property, if wrongly used, could be fatal.

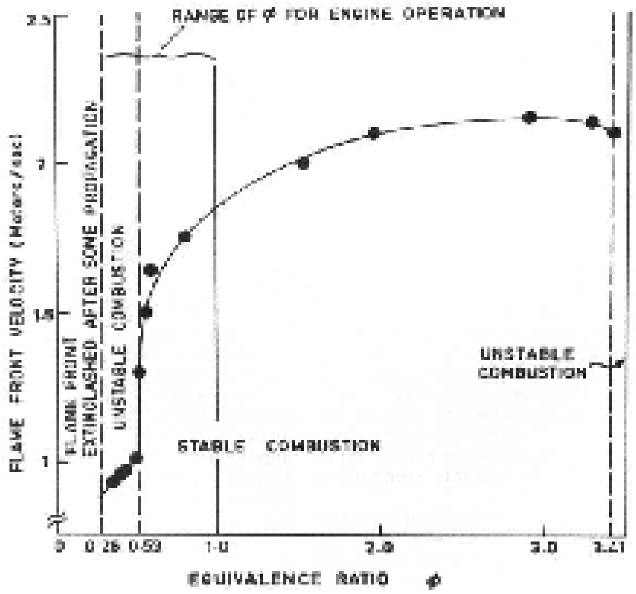

Fig. 1 Ranges of equivalence ratio for engine operation

The ignition energy required to ignite an air-fuel mixture depends very much on the air-fuel or equivalence ratio—hydrogen has an extremely low ignition energy compared to gasoline. This is a very crucial property. On one hand, the low minimum ignition energy enables the conventional ignition system to be effective with a very low energy spark whereas at the same time it makes the system susceptible to surface ignition. Surface ignition is a highly undesirable combustion phenomenon because it precipitates flashback, pre-ignition and rapid rates of pressure rise. Based on the lower flammability limit, hydrogen seems to be superior to gasoline, but a small leakage from a hydrogen operated system brings in the problem of safety. As far as the quenching distance is concerned, hydrogen combustion which can be initiated with a low energy spark, becomes difficult to quench. Because of the smaller quenching distance of hydrogen, a flame in a hydrogen-air mixture escapes more readily past an even nearly closed intake valve than a hydrocarbon-air mixture.

The minimum ignition energy required for ignition (0.02 mJ) of a hydrogen-air mixture has often been responsible for the fresh charge being ignited and thereby causing a flame that propagates through the induction system giving rise to backfire. The simplest method to avoid backfire is to ensure the absence of combustible mixture in the intake manifold. A reduction of temperature level could also prove very effective. On the other hand, conditions leading to pre-ignition could be disposed of by preparing a late hydrogen-air mixture. These can be achieved by various methods such as (i) use of leaner mixtures, (ii) exhaust gas recirculation, (iii) intake air cooling (by liquid hydrogen or by water) and (iv) reduction of valve overlap.

3. FUEL INDUCTION TECHNIQUES (FIT)

The fuel induction techniques have been found to be playing a very dominant and sensitive role in determining the performance characteristics of an I.C. Engine. The 'FIT' for an S.I. engine can be classified into four categories such as Carburetion, Inlet Manifold Injection, Inlet Port Injection and Direct Cylinder Injection. These conventional methods of 'FIT' could also be applied to engine operation with a non-conventional alternative fuel, such as hydrogen. Of these methods; carburetion by the use of a gas carburettor has been the simplest and the oldest technique. In a gasoline-fuelled engine, the volume occupied by the fuel is about 1.7% of the mixture whereas a carburetted hydrogen engine, using gaseous hydrogen, results in a power output loss of 15%. Thus, apart from eliminating unwanted combustion symptoms, fuel induction techniques have also been quite effective in compensating for the power loss. Injection of hydrogen into the inlet manifold offers an alternative to the conventional load control method by throttling. This method uses the typical properties of hydrogen fuel (such as wide flammability limits) to a point of advantage. It also possesses the ability to initiate fuel delivery at a timing position sometime after the beginning of intake stroke. The system could be so designed that the intake manifold does not contain any combustible mixture thereby avoiding extreme situation leading to undesirable combustion phenomena. In a carburetted engine system, the valve overlap between the exhaust and the intake stroke can bring the fuel-air charge into contact with the residual hot gases. However, if by any chance pre-ignition does take place during intake stroke, it will have much lesser consequence as compared to that occurring in a carburetted engine. Some investigators have also carried out research on intake port injection. In such a system both air and fuel enter the combustion chamber during the intake stroke, but are not pre-mixed in the intake manifold.

Direct cylinder injection of hydrogen into the combustion chamber does have all the benefits of the late injection as characterized by manifold injection. In addition, the system permits for fuel delivery after the closure of the intake valve and thus, intrinsically precludes the possibility of backfire. However, as described later, the injection system will have to cater to some stringent requirements in respect of the severe thermal environment which the injector is bound to encounter. Besides, all the mechanical parts which form part of the injection system must be able to withstand such a high pressure, say to the tune of about 100 atm. When considering a practical automobile, maintaining a high pressure such as about 100 bars, in a vehicle for onboard storage methods raises serious problems. However a detailed discussion on vehicular storage methods is beyond the scope of the paper.

4. ACHIEVEMENTS AND GAPS

Researchers throughout the world have been working persistently for decades and hence most of the benefits and problems of hydrogen engines have already been identified.

A definite conclusion which can be drawn from these research results is that the undesirable combustion phenomena have greatly impeded the practical achievement of a common hydrogen-fuelled autovehicle: and the mode of fuel induction from one method to other has very seriously influenced the situation.

In the earliest phase of hydrogen engine research Ricardo [1], had adopted the carburetted technique, primarily with a view to achieve hydrogen-fuelled engine operation. Ricardo is reported to have encountered the problems of "popping back into the carburettor" and was unable to get rid of this problem even at the compression ratio as low as 3.8. Thus he concluded hydrogen to be impractical for most uses.

Efforts were made to ensure elimination of backfire and pre-ignition phenomena caused by free floating carbon particles, carbon deposits and cylinder hot spots. Conditions suspected to be promoting backfire were deliberately created inside the engine cylinder to arrive at definite conclusions. King used "cold spark plugs" and an aged sodium filled valve. Hydrogen engine research did suffer a setback for a long period because of the availability of sufficient petroleum-based fuels. However, in the latter part of the 1970s when the dual problem of petroleum fuel depletion and environmental pollution assumed significance, hydrogen was again tried as an alternative fuel by many investigators for its infinite source potential and nonpolluting characteristics. Because of the simplicity of engine configuration obtained only by the use of a gas carburettor and the requirement of low pressure for hydrogen induction, these investigators probably used hydrogen carburetion as the FIT.

As emphasized earlier, these carburetted versions of the engine systems, apart from developing low power outputs (as compared to the gasoline-fuelled engines) also exhibited severe operational combustion-related problems such as backfire, pre-ignition, combustion knock and rapid rate of pressure rise. It is the teething problem of backfire (which persisted in the carburetted hydrogen engines, and was extremely difficult to eliminate in most operating engine conditions) which prompted several other researchers to try out alternative modes of fuel induction. Swain and Adt [2] tried out a method of "Hydrogen Induction Technique" (HIT) in which hydrogen was supplied through the passage on the intake valve. Their reports verify the effectiveness of HIT over conventional carburetion technique in overcoming backfire and pre-ignition problems.

Lynch [3] has suggested "Parallel Induction" which has proved successful in getting over the problems associated with backfire. Broadly speaking, this is a method similar to intake port injection. He has also reported another method of hydrogen induction technique through a copper tube placed inside the air intake port. A sleeve-type valve-seat mechanism built on the original intake valve is used to control the system. This method of delayed hydrogen admission proved quite effective in suppressing the undesirable combustion phenomena.

Bindon et *al.* [4] successfully tried out a novel technique of providing a quality-controlled mixture through a lean burn carburettor specifically developed for hydrogen operations. Timed port injection was also tried successfully by these researchers to eliminate the presence of the combustible mixture in the intake manifold in the proportions that could cause backfire. Varde and Frame [5, 6] developed a system of electronically controlled fuel injection in which injection was designed to take place close to the intake valve when the valve was

Open. This method was adopted chiefly to ensure the lack of hydrogen-air mixture entering the engine. Research results of these investigations show that it was thus possible to achieve higher thermal engine efficiency as compared to the carburetted operation of either gasoline or even hydrogen. In some combustion related studies he also compared the variation of rate of pressure rise as well as the flame speed with respect to equivalence ratio as shown in Figs 2 and 3.

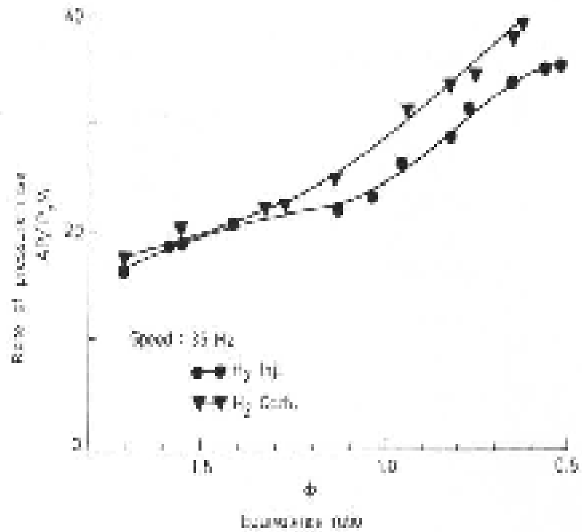

Fig. 2 Pressure variation vs equivalence ratio

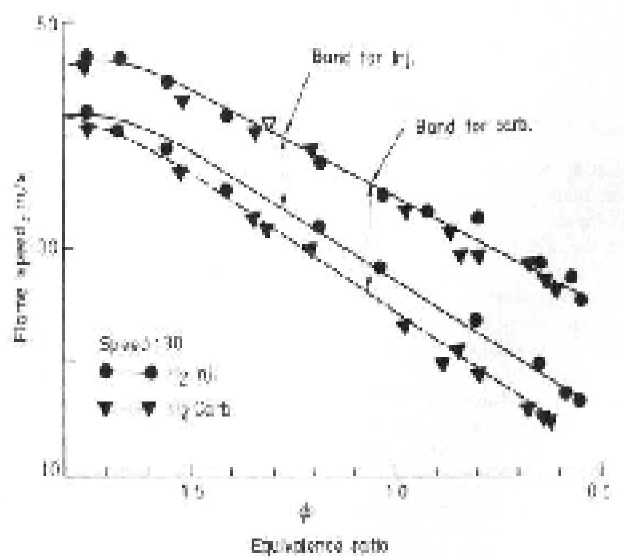

Fig. 3 Flame speed vs equivalence ratio

McCarley and Van Vorst [7] carried out extensive experiments on a hydrogen engine adopting both a port injection and direct injection system. The engine system configuration, designed to ensure quality control, did prove quite effective in ensuring a backfire free operation. It was further established that the fuel delivery in the injection system was not solely governed by the intake air flow. Hence it is always possible to optimally design a system based on various engine parameters and thus avoid conditions leading to backfire. As far as pollution aspects are concerned it has been found the $(NO)_X$ formation could be minimized by a precise control of equivalence ratio. Figure 4 shows the performance parameters of an electronic hydrogen injection system developed by McCarley and Van Vorst.

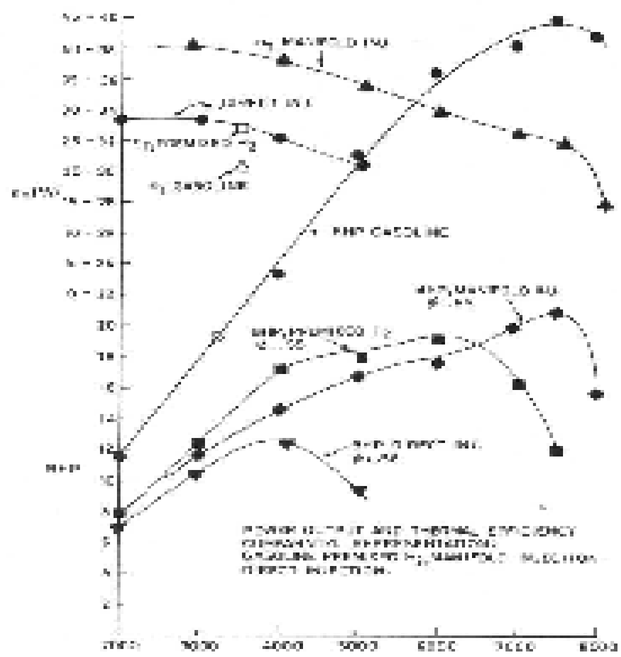

Fig. 4 Performance parameters of manifold and direct injection hydrogen engine

The other two methods such as timed manifold injection and low pressure direct cylinder injection were subjected to elaborate experimental investigation. Both these methods, by definition, should preclude the problems of flashback and pre-ignition either by supplying hydrogen gas directly into the cylinder after the closure of the intake valve (in **LPDI)** or by introducing hydrogen at an appropriate time in the manifold and at an appropriate location so that hydrogen is introduced after the potential hot spots are cooled again. Two different designs of injection systems were developed for carrying out the experiments. It was observed that, compared to **LPDI,** the TMI system required a less sophisticated design of the injector, as the former needed the injector to be capable of surviving in the severe thermal environment of the combustion chamber. Therefore leaking of the injector tip seemed to be a constant problem in most of the preliminary experiments which, of course, could ultimately be eliminated by proper choice of material subjected to heat treatment processes. On the other hand such a problem almost did not exist in a TMI system. In addition to this, LPDI seemed to exhibit problems of incomplete combustion, probably due to such a short time allowed for the mixing of hydrogen and air to take place. Timed manifold injection was observed to have possessed certain specific advantageous features with regard to other modes of fuelling techniques. In the entire range of experimental investigation hydrogen was supplied to the engine system in a gaseous phase thus leading to conditions of uniform and rapid mixing.

A series of exhaustive experiments were conducted earlier on the same engine using carburetion as the fueling mode. A comparative evaluation of both carburetted and TMI configuration indicated that TMI version of the engine was able to achieve an increase of 4.2% in indicated thermal efficiency and almost a 20% rise in peak power output. The experimental arrangement shown in Fig. 5 exhibited a unique operational feature. It permited the flexibility of adopting diesel-like quality governing and achieving the efficiency of a diesel engine while developing a specific output comparable to an S.I. engine.

The technique of direct cylinder injection has been tried as an effective step against the undesirable combustion phenomena since very early phase of hydrogen engine research by Erren. The hydraulically operated hydrogen injection system developed by Varde and Frame [6] was also applied to a direct cylinder injection configuration with the injection scheduled to occur during the compression stroke. Besides exhibiting good performance characteristics the system is reported to have given lower levels of pollutants as compared to that of gasoline fuelled spark ignition engine, Homan [8] carried out experiments on a hydrogen-fuelled engine using a LIRIAM (Late Injection, Rapid Ignition and Mixing) technique. A large number of perating parameters and their influence on performance, exhaust emission as well as combustion characteristics of the engine were thoroughly investigated. Operational characteristics with conditions of the least pollution and minimum undesirable combustion symptoms were experimentally evaluated. Figure 6 shows the injector developed by Homan. However, this work clearly describes the inherent problems that arose in the design and development of the injector.

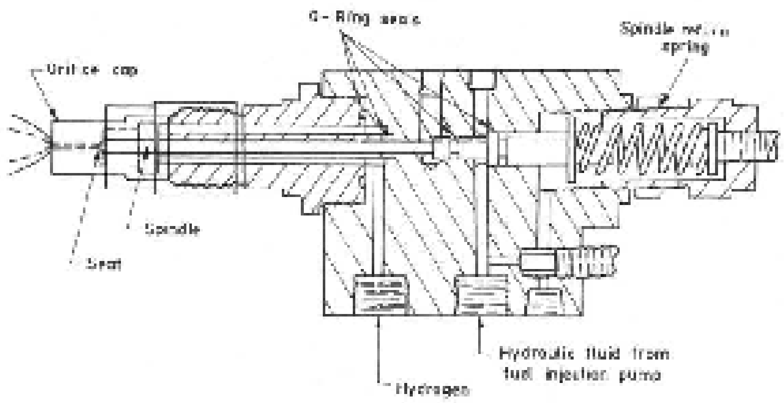

Fig. 6 The hydrogen injector

5. COMPRESSION IGNITION ENGINE

Ikegami *et al.* [9] investigated hydrogen combustion in a conventional swirl chamber type diesel engine. It has been reported by these investigators that hydrogen-fuelled diesel combustion could be achieved to a limited extent because of the auto-ignition characteristics of the fuel. An interesting observation made in this work was hat once the swirl chamber was vitiated either by one small leakage or by a pilot injection, smooth combustion could be attained. A pilot injection ensures ignition and also reduces the ignition delay to some extent. A small leakage from the injector most often exhibited similar effects. Sometimes pronounced improved effects have been observed on the ignition. It has found that a definite amount of leakage, once established, permitted the engine to run without any symptoms of knocking over a fairly wide range of operation. However, an excessive introduction of the preliminary fuel may cause auto-ignition by itself thus giving rise to rough combustion. In this work, the conditions required to ensure smooth burning have been thoroughly studied by varying the amount and time of pre-injections and the quantity of fuel leakage.

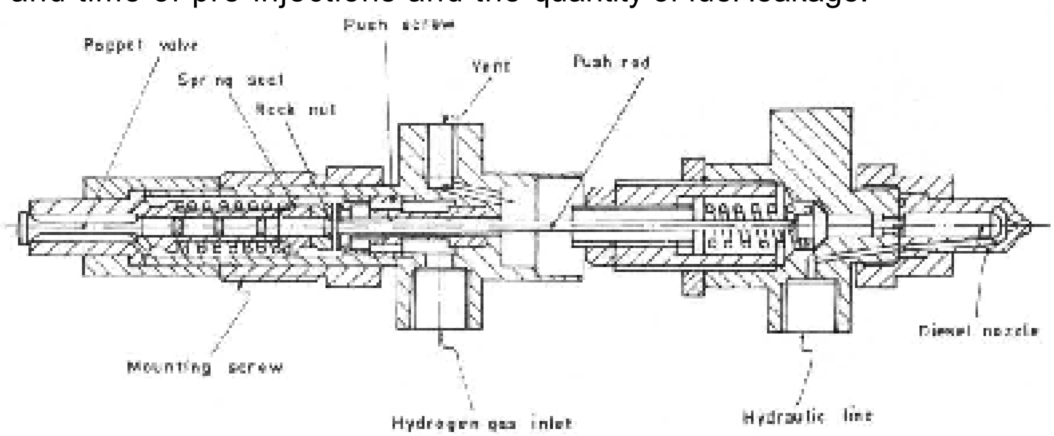

Fig. 7 Hydraulically actuated hydrogen gas injector

In another attempt a closed cycle engine system was simulated by supplying a 21 % oxygen mixture to the test engine. The engine operation was observed to be extremely satisfactory without any ignition aid. The engine system operating with an oxygen-argon charge exhibited substantial gain in indicated thermal efficiency Figure 7 shows the hydrogen gas injector.

7. CONCLUSIONS

The consistent research efforts and their outcome clearly show that a mixture formation method plays a decisive role in the practical emergence of a future hydrogen specific engine.

Future developments of such engines depend a lot also on the mode of storage and supply system. Using cryogenic hydrogen supplied from a liquid hydrogen tank has the prospects of increase in volumetric efficiency and thus the power output. It also reduces the specific fuel consumption as well as the level on NO_x emissions. The limits of backfire are further lowered.

Late fuel injection, on the other hand, is a very promising fuel induction technique as it does preclude the possibility of backfire, the century-old problem which has been bothering the hydrogen researchers. This technique could also be adapted to both two stroke as well as four stroke engines.

An appropriate TMI system designed specifically on the basis of hydrogen's combustion characteristics for a particular engine configuration ensures smooth engine operational characteristics without any undesirable combustion phenomena. However, all those characteristics have been evaluated in converted engines. So, an integrated fuel induction and storage method must be designed for a hydrogen-specific engine which can embrace the benefits of good performance, least exhaust ideal engine system.

8. REFERENCE

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