Autoignition of Natural Gas Fuelled Engines -A Review of its Possibilities

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Abstract : This paper outlines a general review of the different possibilities to upgrade power output and efficiency of conventional natural gas fuelled engines to the diesel fuelled levels. This includes a brief introduction on various aspects and feasible ways of how to achieve "diesel-like" combustion in current natural gas engines. This promises to be an interesting area worth to be researched for furgher potential development.

Keywords : *Autoignition, Natural Gas.*

INTRODUCTION

Conventional natural gas fuelled engines have a considerable economic advantage over their diesel and gasoline engines counterparts, and they tend to be technologically innovative and also more environmentally friendly. Natural gas is already chemically ready for use and requires no preliminary treatment. Another advantage of natural gas is its wide flammability limits, especially to the fuel-lean side where ignition of natural gas can occur in the presence of more than 200% theeoretical air [1]. Operating in this regime will ensure improved fuel economy and lower emission level. However, this advantage will no longer be enough on its own and may be challenged, and may even decline as a result of the completion for the advanced diesel engines in their next development stage.

As a consequence, the only way natural gas fuelled engines can compete is to improve their shaft efficiencies. This is also because conventional spark-ignition engines technology does not allow the means to achieve "diesel-like" combustion through the direct injection of high-pressure natural gas into the cylinders.

This paper briefly discusses the issue of direct-injection of high-pressure natural gas and a basic study on the various conventional approaches to ignite natural gas, with respect to their possibilities and changes leading to "diesel-like" combustion or autoignition, based on the basis of engineering concerns.

The ramifications of implementing this conceptual development will not only raise the gas engine efficiency and power output, but also the ability to take advantage of future advances in diesel engine technology, such as reducing heat loss through improved combustion chamber insulation.

NATURAL GAS

Basically, natural gas consists of carbon and hydrogen, mainly in the form of methane, CH_4. Having a simple and stable molecule it is extremely resistant to self-ignite and thus has a low cetane rating. It is also able to mix homogeneously with air to produce a combustible mixture, and is excellent for use in "lean-burn" mixtures which are comparatively less polluting. All these characteristics have made natural gas an instrinsically ecological and environmentally friendly fuel. Therefore, it comes close to the concept of an ideal fuel for this generation and the generations to come.

The octane rating of natural gas is approximately 130, this indicates that spark-ignition engines running on natural gas can operate at compression ratios up to 16:1 (normal compression ratios for such engines is between 7.5:1 to 9.5:1) without "spark-knock". Such a tremendous rise in compression ratios will certainly bring about power improvement of 25% to 40% over that of today's low compression gas engines[2].

Being able to achieve a relatively high compression ratio in a natural gas engine is important. The higher ratio causes an increase in thermal efficiency, which in turn reduces fuel consumption. While refering to the general trends revealing the relationship between cetane number, temperatures, fuel type and ignition type shown in the chart generated by Haddad and Watson [3], it was reflected that fuels having cetane number lower than 25 will exhibit a significant feature in ignition delay. Thus it is not hard to perceive that the considerable delay in ignition with natural gas is characterised by its low cetane number.

DIRECT-INJECTION IN NATURAL GAS ENGINE TECHNOLOGY

Power output of the current natural gas fuelled engines, utilizing a carburetted, spark-ignited combustion system (Otto-cycle) is limited by knock of the homogeneous fuel/air charge to approximately 1250 kPa (180 psi) brake mean effective pressure [4].

The knock problem and its related power limitations could be eliminated by directly injecting high-pressure natural gas up to 20000 kPa (3000 psi) into the cylinder near the top dead centre with a gas injection, incorporating ignition-assist (glow plug is used) to ignite the low cetane natural gas. And this will produce a "diesel-like" autoignition.

By eliminating the knock limit, the direct-injected gas system can utilize higher compression ratios and higher charge air density than the current gas engines, and furthermore, the flow losses associated with the carburetor will also be avoided. Moreover, the future diesel engine technology improvement including insulation can be applied to direct-injected gas engines, but cannot be applied to the current gas engines due to knock limitations.

In conjunction with the above, future improvement in the direct-injected natural gas engine, even accounting for the additional parasitic losses associated with increasing the natural gas pressure with a gas compressor is expected to give a significant improvement in net thermal efficiency.

For the direct-injected natural gas engines, special hardware included an electronic gas injector (similar to the diesel's electronic unit injector), a cylinder head incorporating a glow-plug-ignition-assist system and a compressor in the line of fuel supply will all need to be developed to attain a good combustion of the low cetane natural gas fuel.

The Gas Research Institute of Chicago of U.S.A. revealed succinctly in their Annual Report, that natural gas engine power and thermal efficiency comparable to a diesel are achieveable by incorporating direct gas injection with glow plug ignition assist (DIG/GPIA) during tests on a Caterpillar 3400 series single cylinder laboratory demonstration engine [4]. The DIG/GPIA system will allow the natural gas engine to have power and thermal effiency improvement of up to 50% and 13%, respectively, compared to current natural gas engines.

HYPERGOLIC / SPONTANEOUS COMBUSTION

Hypergolic combustion is a type of ignition and combustion process, in whcih fuel and oxidant pair ignites spontaneously and is rapidly combusted. As a result both the ignition delay and the combustion duration of fuel are negligible. For the purposes of this discussion, the phenomenon of hypergolic combustion can be seen to resemble autoignition/spontaneous combustion. Taylor [5] defines autognition in a fuel-air mixture as a rapid chemical reaction not caused by an external ignition source such as a spark, a flame, or a hot surface.

The hypergolic combustion is a phenomenon which has a promising potential to be applied to a direct-injected natural gas engine. It is aimed at reduction in the ignition delay, improving the quality of combustion, reducing emission levels and increasing overall engine performance.

The primary drawback of most of the listed ignition and combustion alternatives to be discussed in the ensuing section (section 5) revolves aroudn the fact that the bulk of the heat release would be flame speed limited as the flow of natural gas is much slower than gasoline fuel.

Conceptually speaking, the aforementioned problems could be overcome if the natural gas is hypergolically combusted. In another word, prior to injection, if the natural gas is chemically activated, once it is injected it will ignite sponteneously and combustion will occur rapidly. Therefore, if this could be done, the flame speed limitation could be circumvented and the combustion event could be also controlled through the rate of injection. Furthermore, the overall air/fuel ratio and compression ratio could be arbitrarily selected so as to obtain the best trade-off for high efficiency and low emissions.

The basic theory of hypergolic combustion and the experimental results obtained in an engine test fuelled by liquid fuel are presented by Hoppie [6] and Hoppie and Scharnweber [7].

Theoretical results prediction speculated by Hoppie [6] indicated that the ignition delay can be made arbitrarily small and essentially independent of air temperature if the fuel is sufficiently preheated.

As demonstrated by Hoppie and Scharnweber [7], Hypergolic combustion could be realised in a internal combustion engine by means of preheating the fuel. The reduction in ignition delay and increase in combustion rate will result, in conjunction with fuel injection rate and duration control would provide much better control of the combustion event. Therefore, following this, the engine power output, emission levels and engine efficiency can be optimised.

With reference to the above arguements, one can propose that thermal energy can be used as a means of activating the fuel, i.e., as a means to produce fuel radical such as; CH_4 to CH_3, CH_2, H,etc.

In the midst of optimism, engineering problems in handling high temperature fuel must not be ignored and it needs to be resolved before the idea of hypergolic combustion can become [ractical and technically viable.

IGNITION AND COMBUSTION ALTERNATIVES

In combustion, the "reaction" is not a single or even a few-step process; the actual chemical mechanism consists of a large number of simultaneous, interdependent reactions or chain reactions. In such chains there is an "initiating reaction" where highly reactive intermediate species or radicals are produced from stable molecules, i.e., from fuel and air. This is then followed by propagation reactions radicals react with the reactant molecules to form products and other radicals to continue the chain, Heywood [8].

This section presents the possible alternative approaches, having potential to start "intiating reaction", in which more effort is required to evaluate and investigate both theoretically and experimentally each scheme's possibility in leading to "diesel-like" combustion for natural gas engine.

Thermal Energy Activation

The mathematical model developed by Hoppie [6], which predicts that ignition delay is a function of fuel and air temperature, implies that the concentration of chemically active fuel radicals can be significantly increased via thermal dissociation of the fuel by preheating it. Therefore, if the fuel is so activated, it will ignite and be consumed much more rapidly upon injection into cylinder than through fuel injected at ambient temperature.

A major anticipated shortcoming, associated with thermal activation is in the fact that there is a tendency of coke formation if fuels are held at high temperatures for long duration time due to dehydrogenation. Compression heating could be possible to minimise the occurrence of coke formation. Using the process of compression heaitng, i.e. through rapid compression, it is conceivable that the desired radicals could be created and injected prior to the coke formation. Another practical way of eliminating coke formation is through the addition of water to the gas prior to heating.

Catalytically Enhanced Thermal Energy

This criterion is based on the fact that upon employment of some suitable catalyst, chemical reactions can be forced to occur at a temperature lower than normally expected. This is also a practical way to generate fuel radicals at a temperature just low enough to avoid the formation of coke. Other advantages of this scheme are the provision of a sustained combustion with lean mixture and also low pollutant product, owing to more complete combustion.

There are two possible means of modifying natural gas in order to achieve autoignition, and hence combustion, without assistance upon injection into an engine. They are (i) catalytic activation of natural gas and (ii) catalytic activation of natural gas and air. The basic idea behind catalytic enhancement of natural gas rests on the fact that a suitable catalyst can create certain chemical species or active radicals, at a lower temperature than normally would be required if no catalyst is present. Some potential catalysis are MgO, metallic nickle, both alpha and gamma phase Al_2O_3 and SiO_2. This can be accomplished by the introduction of an in-line catalyst chamber at the inlet of the fuel line, in whcih contains the pelletized catalytic materials.

Partial Catalytic Combustion

This concept has been developed in the Jet Propulsion Laborary and Siemens of U.S.A., Houseman and Cerini [10]. Their idea is to improve liquid-fuelled spark-ignited engines by first converting the liquid fuel into a hydrogen-rich gas, in which such a fuel would offer improved effeciency and lower emissions. To convert to a hydrogen-rich gas, the liquid fuel was first vaporized, mixed with a small amount of air, and then allowed to partially combust with the aid of and in the presence of a suitable catalyst. It was found that this could be accomplished without coke formation, and that the product gas was rich in fuel radicals and atomic hydrogen, at an approximate temperature of 66 degree celeius (150 degree F). This product gas would be directly injected into the engines to achieve autoignition, which is the concept of hypergolic combustion.

Compression Ignition

In this concept, compression combustion via preheated inlet air can occur without relying on any external source of ignition in a direct-injected natural gas engine. Having a very low cetane rating compression ignition of natural gas is quite difficult to achieve in a conventional diesel engine without modification of the engine. However, conventional compression ignition can be accomplished via preheated inlet air. This is a very promising method leading to hypergolic combustion. In this case, waste heat given out by engine can be harnessed to preheat the inlet air, either through heat-exchange from colling system, lubrication system or exhaust system.

Electrical Energy Ignition

Theoretically, the establishment of an electric discharge in the natural gas will generate radicals. This may be done by utilizing a corona or an arc discharge. One can anticipate that, even through direct injection of natural gas, spontaneous ignition is still far from reality. The actual heat release would most probably result from flame propagation, which is predicted on the establishment of a sufficiently large flame kernel resulting from the interaction of a rather small portion of the injected fuel with the ignition source. Due to the excessively long combustion duration, low efficiency and high emission could thus be expected.

If methane or natural gas is electrically activated with an arc discharge during injection, negligible ignition delay and rapid combustion are possible. Theoretically, this offers a great practical value. With proper amount of electrical activation, a controlled combustion event could be achieved with accompanying low levels of emission

Photochemical Dissociation

Prior to injection, an ultra violet source could be employed to activate methane by projecting an ultra violet beam into a portion of natural gas to establish chemically active, unstable fuel radicals from stable molecules to enhance the vigour of the combustion.

Pilot Injection

Pilot injection of diesel fuel as a primary means of providing a flame kernel is predicted to be sufficient to ignite directly injected natural gas. However, the profile of flame front for combustion of the gas is the main parameter to control the efficiency and emissions output.

Glow Plug Ignition

A glow plug appears to be quite promising in leading to autoignition in natural gas. It is very similar to a liquid-fuelled, directed, spark-ignited engine or a spark-assist diesel engine.

Plasma Jet Ignition

The concept in this particular type of ignition scheme is borrowed from the technology of the torch ignition engine, in which, charge separation may be achieved by using a pre-chamber for a rich mixture of fuel and air and the main chamber for a weak mixture. The injection system can be used to supply fuel, Benson and Whitehouse [11]. By the creation of a plasma jet of fuel (diesel fuel or just natural gas), or air or both air and fuel in a prechamber, while injecting natural gas into the combustion chamber, natural gas will be ignited by the impingement and interaction with the second jet, i.e., the plasma jet. This ensuing plasma jet is rich, consisting of chemically active species and would create a vigorous reaction within the primary fuel/air mixture. This plasma jet can be attained via electrical discharge in air, fuel, or air/fuel. Under this phenomenon, combustion duration can be greatlh reduced, hence, improved combustion process will result.

Laser Ignition

Instead of using electrode spark plug, a laser beam can be utilised to introduce an intense electric field breakdown in the combustion chamber to ignite the natural gas as it is injected. In this case, a laser beam is focused inside the combustion chamber to create a region of such intense electric field that breakdown of the stable species of fuel occurs.

CONCLUSIONS

Based on hypergolic combustion, a direct ignition incoporating glow-plug-ignition-assist system, the dream of achieving 'diesel like' performance in a conventional natural gas engine is viable through the means of activation of natural gas as mentioned above.

This will not only reuslt in improved power output and thermal efficiency, it also permits the natural gas engine to take full advantage of future advanced diesel engine improvements such as the application of ceramic liner for combustion chamber insulation. With the advent of the low heat rejection diesel engine technology, natural gas as an alternative fuel has become possible offering the advantages of burning low cetane fuel.

With hyprgolic combustion, the combustion event will be completely different from that of spark-ignition or compression-ignition, hence, it is logical to suspect that the injected fuel pattern, heat transfer profile and thus the combustion shape itself should be different.

At this stage, sufficient data are not available to further determine and compare as to which concept/scheme is superior from the engineering point of view.

RECOMMENDATIONS

1. Each of the scheme/approach as well as their amalgam of differnt schemes or 'hybrid' system consisting of the combination of the above mentioned schemes should be experimentally evaluated to determine if they are technically viable to achieve autoignition in the natural gas engine.
2. Improved air turbulence is likely to provide the desired improvement in combustion.
3. As natural gas has high resistant to 'spark-knock', therefore, high compression ratios can be attempted, giving high thermal efficiency, similar to the comparable diesel engine, which in turn reduces the fuel consumption.
4. Multiple plugs with different configurations can be tried on the diameter of each cylinder to achieve optimal combustion rates, and leading to higher efficiency.
5. Generally, a three-way catalytic converter can be fitted to a natural gas engine to cut down the amount of carbon dioxide, carbon monoxide, oxides of nitrogen and nonmethane hydrocarbons in the exhaust emission.
6. By the use of a small prechamber with each cylinder that burns a rich mixture of natural gas and air, which is ignited by a spark plug, and on the

other hand, the main portion of the combustion chamber burns a lean mixture, which is ignited by the burning gases in the prechamber, combustion will occur at lower temperatures than usual. Thus reduction of the nitorgen oxides could be achieved.

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