DUAL VERSUS SINGLE SPARK PLUG: A CRITIQUE

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ABSTRACT

Dual spark plugs are occasionally employed on certain modern Spark Ignited (SI) engines, viz. lean burn engines. Their benefit has generally been noticed in the operating conditions when fuel-air mixture is very lean, or when a larger proportion of EGR has been employed, or during the part load conditions and so on. An extensive literature survey has indicated an interesting spectrum of reasons for gains due to the dual spark plug. A consistent explanation is found to be missing which can describe the behaviour of the engines with single versus dual spark plugs.

There are quite a few researchers who merely state that a dual plug engine gives better results than a single plug engine without giving the exact cause of the same. Some investigators have argued that due to the shorter flame travel distance with dual plugs the combustion is faster, whilst some, attribute the gains due to change in the flame shapes or speeds. The present author suggests that is not the case because no significant gains have been noticed due to dual plug system for full throttle conditions. A hypothesis is therefore proposed by the author that the dual plug engine will perform better than the single plug engine only when the engine is operating at conditions unfavourable to ignition. This is attributed to the increased probability of ignition and combustion stability with dual plugs when compared to comparable engine with single plug system during such conditions. It is believed that the hypothesis, if validated, will form the basis of the explanations to the behaviour of certain dual plug engines and therefore assist in arriving at a consistent and acceptable description of the behaviour of the engine with dual versus single spark plugs.

INTRODUCTION

Several methods are being considered by the automotive engine designers which could improve the fuel economy and emission characteristics. These methods include possible use of alternative fuels to diesel and petrol, and improvements in the utilisation of the conventional fuels. In the later method, diesel engine is more promising because of its lower fuel consumption and lower carbon monoxide (CO) and Hydrocarbons (HC) emissions when compared with SI engine. However, the petrol engine is still preferably used in certain applications requiring low weight, size, initial cost, noise and vibration levels or those with low duty factor. Hence it is possible to conserve the existing petroleum reserves over a longer period, reduce operational cost resulted from the increasing fuel price, and protect the environment from automotive pollutants emission mainly if the petrol engine is improved. The Lean Burn Petrol Engine (LBPE) is believed to be a promising SI engine that could satisfy both the improved fuel economy and low pollutants emission requirements. Improvements in lean combustion characteristics through charge stratification, improved combustion chamber and ports designs, increasing ignition system power, and use of dual spark plug have been reported. It is the later approach in lean combustion which is the subject of this paper.

Significant effort has been put by various researchers to study the concept of dual spark plug ignition in order to meet the pressing necessity of low fuel consumption and exhaust emission. Most of the reported research works were aimed at efficient engine operations with very lean fuel-air mixtures or with low load, or with a larger proportion of Exhaust Gas Recirculation (EGR), and so on. Although a considerable amount of data has been generated in these works and which generally indicate the mentioned gains, a consistent explanation is found to be missing which can describe the behaviour of SI engine with single versus dual spark plugs. There are some works, where it is merely stated that a dual spark plug engine gives better results than a single plug engine without giving the exact cause for the same. In other works it is argued that due to the shorter flame travel distance with dual ignition the combustion is faster and thus, the efficiency increases. While in some, the gains in a dual plug system are attributed to change in flame shapes.

In the present paper the author states that such is not the case and goes on to propose his hypothesis regarding the exact cause of the benefits due to the dual plug system.

THE HYPOTHESIS AND ITS BASIS

A dual plug engine is expected to give better results than a single plug engine mainly when the conditions in the combustion chamber are not very favourable for ignition, and consequent development of a flame kernel, viz., operating conditions when a larger proportion of EGR is employed, or when the fuel-air mixture is very lean, or, during part load conditions (such conditions hereafter would be referred to as "conditions unfavourable to ignition"). The engine operating at these conditions have poor mixture quality and they are difficult to ignite. Having two sources of ignition in a dual plug engine at conditions unfavourable to ignition means that the probability of the existence of gases with good mixture quality near the spark gap at the time of spark ignition is higher, and thus chances of misfiring are less when compared to a single spark plug engine.

When the fuel-air mixture is in an environment conducive to flame initiation, away from misfire, such as, at Wide Open Throttle (WOT) conditions, or when operating at, or near, stoichiometric fuel-air mixture, and so on (such conditions would be hereafter referred to as "conditions favourable to ignition"), no gain in power output is expected to be noticeable with dual versus single plug engines if the later is allowed to ignite earlier. In other words, ignition is equally probable in both dual and single plug systems when operating both engines under conditions favourable to ignition. However the so-called difference in performance between single and dual plug engines as noticed by other researchers is generally because the ignition timing was the same for both the engines.

EXPLANATIONS GIVEN IN OTHER RESEARCH REPORTS AND THEIR CRITIQUE

In the work of Piccone et. al [1] the gains with dual plug engine are attributed to the decrease in both the delay period and combustion duration - to faster burning. The explanation of the engine behaviour with dual versus single ignition system is quoted from the report as follows:

" .... the twin ignition halves the combustion delay and improves the ability to ignite leaner mixtures. .... Always in comparison to a mono-spark similar engine, the twin ignition reduces the combustion angle and makes it less dependent on the engine revs.
The first two positive effects are certainly due to higher flame surface and to the shorter distance which has to be covered by the flame travel.

.... In conclusions the twin ignition produces a faster burning rate....".

Figs. 1, 2, and 3 show the results obtained by Piccone et. al as reproduced from Reference [1], where they are Figs. 7, 8, and 10 respectively.

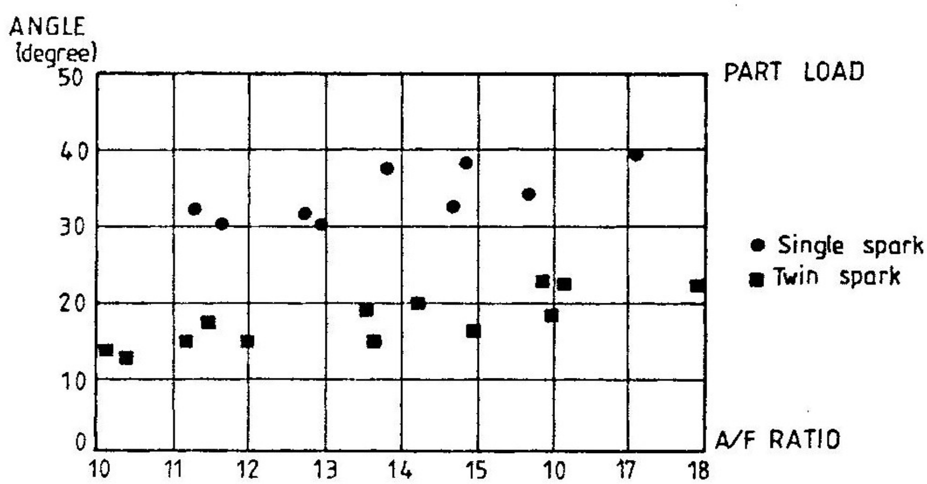


Figure 1 Combustion delay versus A/F ratio

The opinion of the current author is that since both the single and dual plug engines were ignited at the same timing, the later is liable to show some improvement because it behaves as if it was ignited earlier. If the spark timing of the single spark plug engine was relatively more advanced , the benefits could have been not as significant and especially at operating conditions chosen in the study (full load or with air to fuel ratio range of 12:1 to 18:1). However, although the fuel-air mixture is not very lean, still a slight increase in the ability to ignite leaner (also richer) mixture is noticeable with the dual plug system. This indicates the reduced chances of

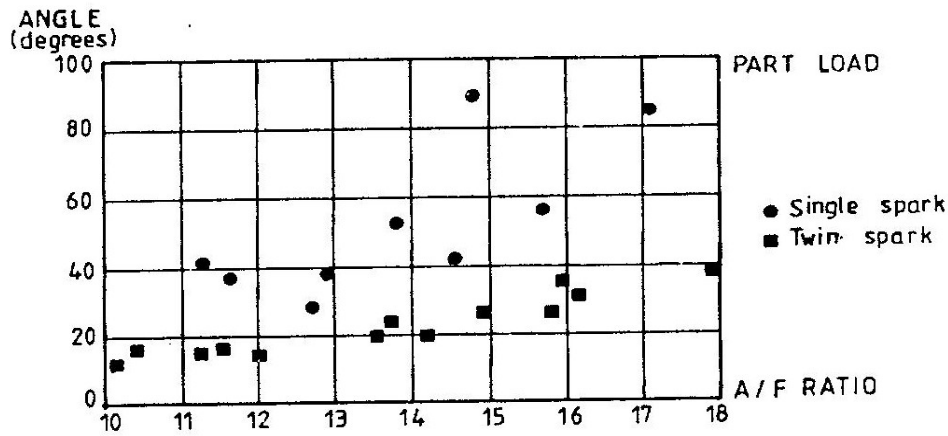


Fig. 2 Combustion angle versus A/F ratio

misfire with the twin ignition system when attempting to operate away from stoichiometric fuel-air mixtures.

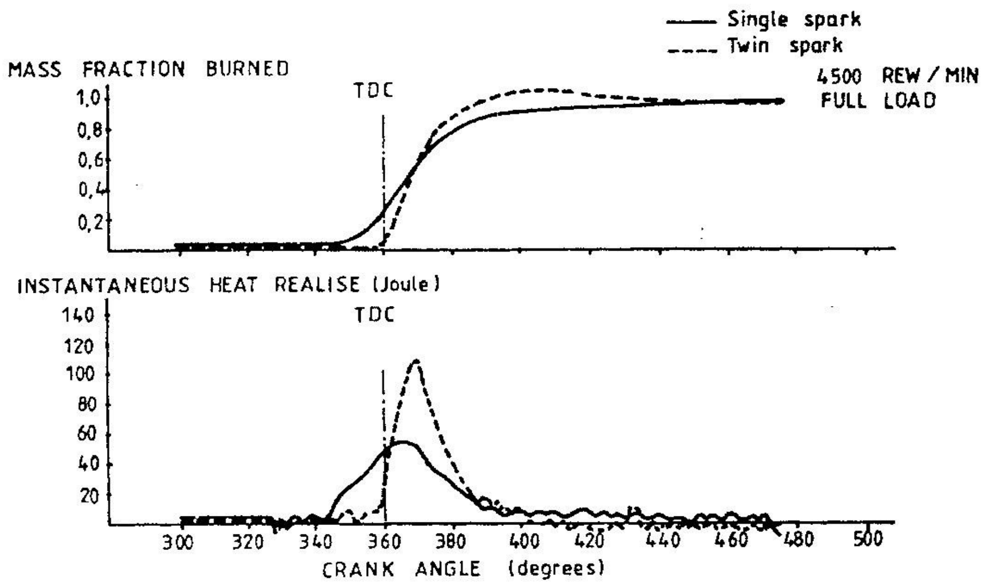
However, a more proper analysis of the dual versus single spark plugs engine behaviour could be achieved if the conditions of both the engines were maintained essentially the same, and the difference be only on the number of spark plugs. In the work of Piccone et. al, it is not clear whether this was the case. From its text it seems that by twin spark engine it is meant the Alpha Romeo, 4 cylinder in-line family engine (which is termed as the single spark engine) modified to incorporate:

- a new aluminium cylinder head with a more compact hemispherical combustion chamber, higher breathing area due to larger intake valve, and optimised inlet port to obtain higher flow rate.

- variable valve timing for optimisation of low load and WOT conditions.

- twin spark plugs ignition.

- electronic control of valve timing and twin ignition.



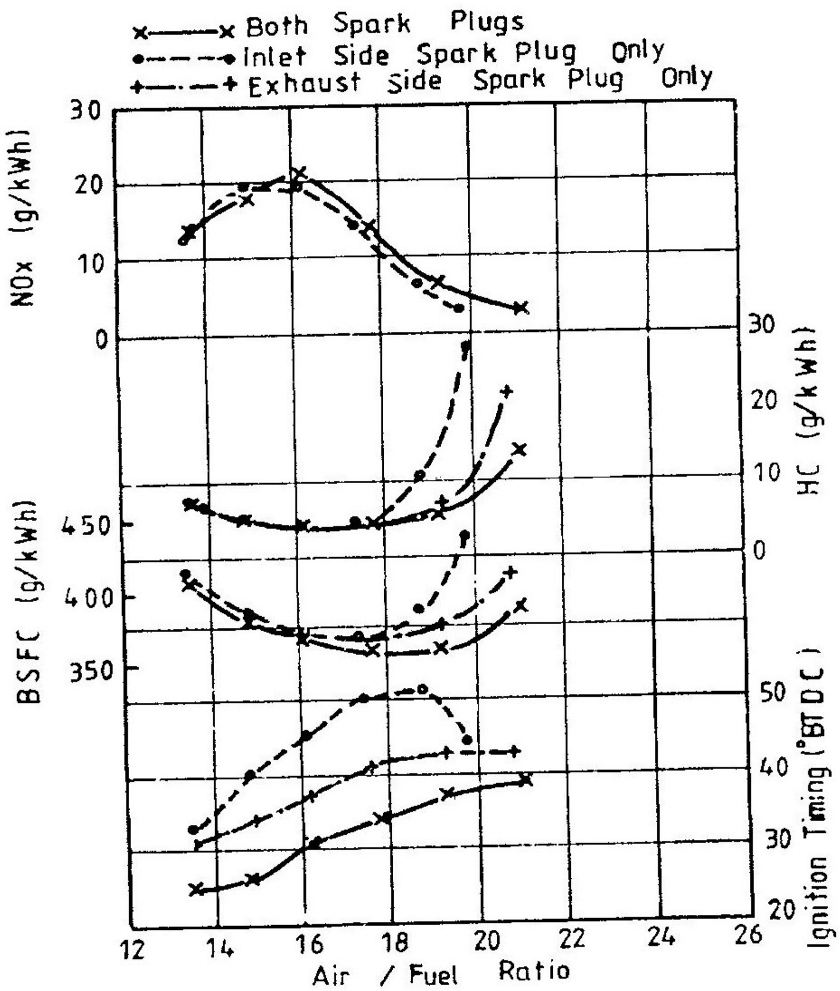
Condition:

Speed 4500 RPM
Full Load
MBT

Fig. 3 Mass fraction burned and instantaneous heat release

The results in the work of Piccone et. al therefore, do not seem to indicate the exact contribution of a dual ignition system. The faster burning rates demonstrated with the twin spark engine (Fig. 3) are probably the results of increased charge density due to the larger intake valve, and the more compact combustion chamber used in conjunction with the dual plug system. Because of the increase in the concentrations of the reactants due to higher charge density, the flame velocity might have increased too, to enhance the mass burned rate further. The use of a more compact combustion chamber should have also reduced the heat losses to the walls as a result of the reduced surface to volume ratio. All these facts might have contributed in arriving at the results shown in Fig. 3.

No explanation is given in the work of de Boer and Grigg [2] to the behaviour of the engine with dual versus single plugs. However, the obtained results indicate the contribution of a dual ignition system as it can be seen from Fig. 4.



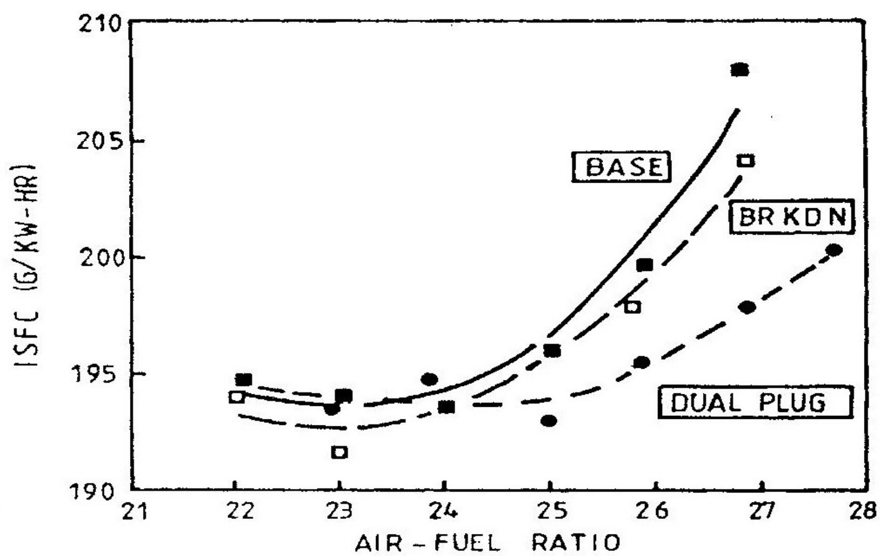
RICARDO HYDRA 0.5 LITRE 8.9 CR
NEBULA COMBUSTION CHAMBER
HELICAL PORT - Rs 1.7
MIXTURE RESPONSE - 2400 REV/MIN
2.5 BAR BMEP

Figure 4 The effect of plug position

The results shown in Fig. 4, (reproduced from the report of de Boer et. al., where it is Fig. 3) can be explained with the help of the hypothesis suggested by the author of the current paper as follows:

It is observed that there is no gain with the dual ignition system until it becomes leaner than air-fuel ratio of 18:1, when the mixture condition is unsteady and quite unfavourable to ignition. This fact, together with the noticed shift of the minimum Brake Specific Fuel Consumption (BSFC) towards leaner fuel-air mixtures, the ability to ignite leaner mixtures, and lower HC emission testify the exact contribution of the dual spark plug system in that engine. It is evident that the combustion stability has increased with dual ignition from the fact that, at such difficult to ignite fuel-air mixtures (air-fuel ratio greater than 18:1), ignition is more probable with the dual versus single plugs engine, to result in lesser number of misfiring cycles.

In the study of Anderson [3], premixed propane was used as the test fuel to investigate the effect of ignition power on fast burn engine combustion. The following results were obtained.



Condition:

Speed: 1500 RPM
9.07 kg/hr Airflow
MBT Spark Advance

Fig. 5 Indicated specific fuel consumption (ISFC) as a function of Air/Fuel ratio

Anderson explained the results given in Fig. 5, and I quote, as follows:

"The dual plug system has the best stability .... This is directly related to the faster initial burning rate as there is less time for perturbations to affect the combustion process between the spark and the time of peak cylinder pressure.

.... Increasing the initial burning rate with dual plugs extends the minimum in the lean ISFC by two air/fuel ratios. This is due to an enhancement of the initial burning rate which improves combustion stability with respect to the other system tested."

The discussion here will be restricted only to the comparison of BASE plug which is a conventional spark plug and DUAL plug system which contains two BASE plugs.

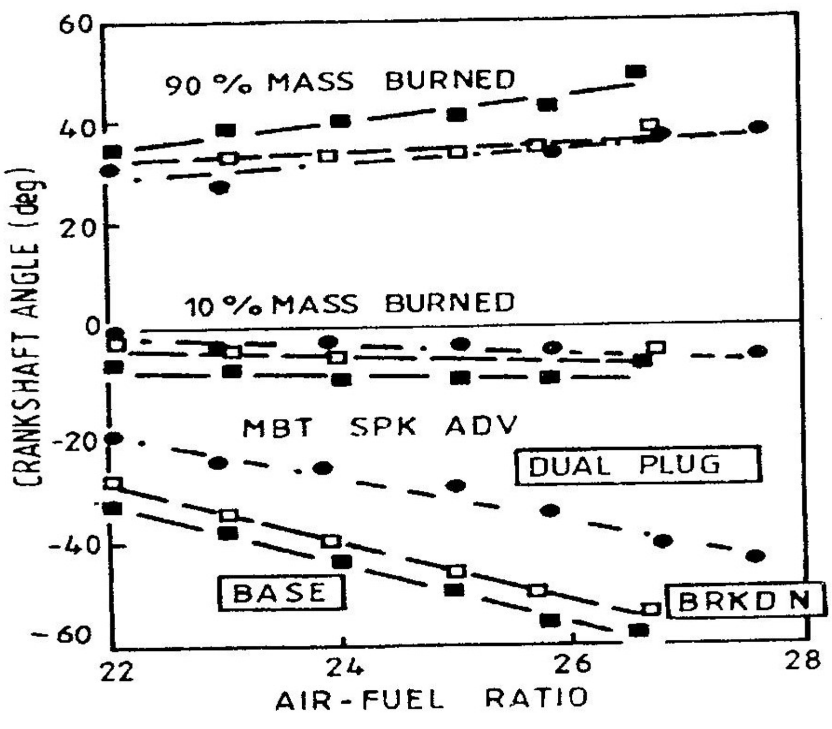


Fig. 6: MBT spark advance requirement and burn time characteristics

Figs 5, 6, and 7 have been reproduced from reference 3 where they are Figs 13, 14 and 15 respectively. It can be seen from Fig. 5 that the dual plug system shows gain in fuel economy only at very lean mixture, the minimum ISFC has shifted to a much leaner air-fuel ratio, and the lean limit has been extended. All these facts may be attributed to poor mixture quality which is a result of operating at very lean fuel air mixtures. This might have caused cycle to cycle variations in the mixture at the spark gap during the time of ignition, and hence poor combustion stability as it can also be seen in Fig. 7. Having two spark plugs under such conditions unfavourable to ignition increases the probability that an ignitable mixture will reach at least one spark plug.

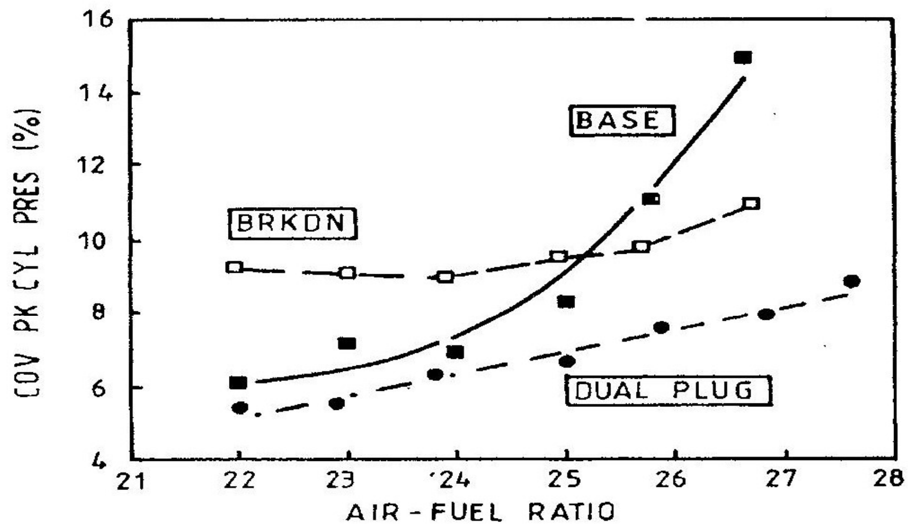


Fig. 7: Combustion instability as a function of air/fuel ratio for the data of Fig. 5.

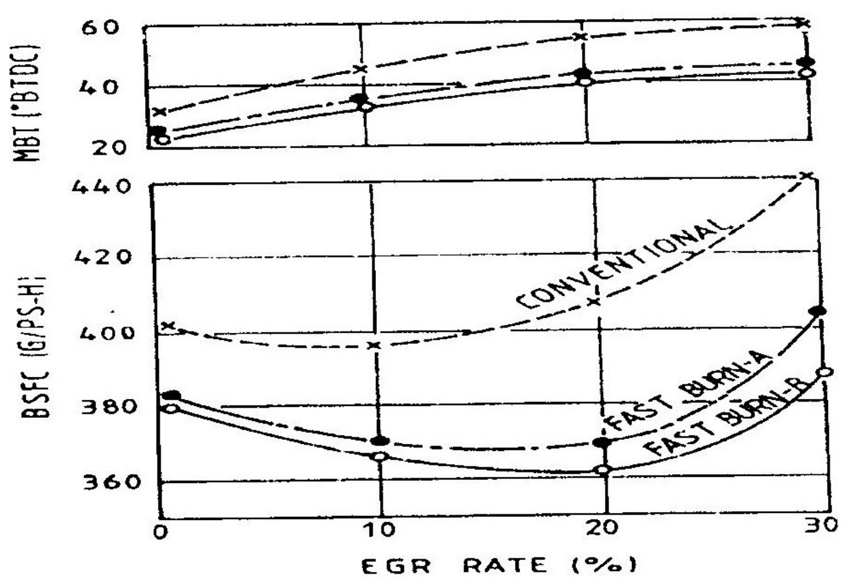
The initial burning rate of the dual plug system does not have significant impact on its combustion stability as reported by Anderson, and especially if the BASE plug (single plug) engine was ignited earlier as it was the case in that work. It can further be seen from Fig. 6 that, at the air-fuel ratio of 22:1, although the duration required to burn 10 per cent of the mass is lower with the dual plug when compared to the BASE plug, the time required to burn 80 per cent (10 - 90 per cent) of mass are comparable in both the cases, and the difference in combustion duration (10 - 90 per cent of mass burned) becomes significant only when the fuel-air mixture is made leaner.

It is obvious from the ongoing discussion that it is the reduction of misfiring cycles, because of the less chance of their occurrence with the two sources of ignition, which mainly determine the demonstrated gains of dual versus single plugs. As it can be seen, the hypothesis put forward by the current author also clearly explains the results of the work of Anderson.

Harada et. al [4] mentioned in their work, and I quote, that:" Use of two spark plugs is intended to achieve fast burn combustion by shortening the distance of flame propagation.

.... The time required for combustion is remarkably reduced by two point ignition even with 20 % EGR, it is almost equal to that of the conventional combustion system without EGR".

Figs. 8 and 9, and Table 1 are depicted from the work of Harada et. al for discussion. They correspond to Figs. 13 and 14, and Table 3 of Reference 4 respectively.



Condition: MBT, 2000 RPM, 2.2kg, A/F15.0

Fig. 8: Improvements in fuel consumption with fast burn system

It is seen from Fig. 8 that the fuel economy for both the "fast burn" engines has improved significantly, when compared to the conventional engine for the whole range of Exhaust Gas Recirculation (EGR) rate.

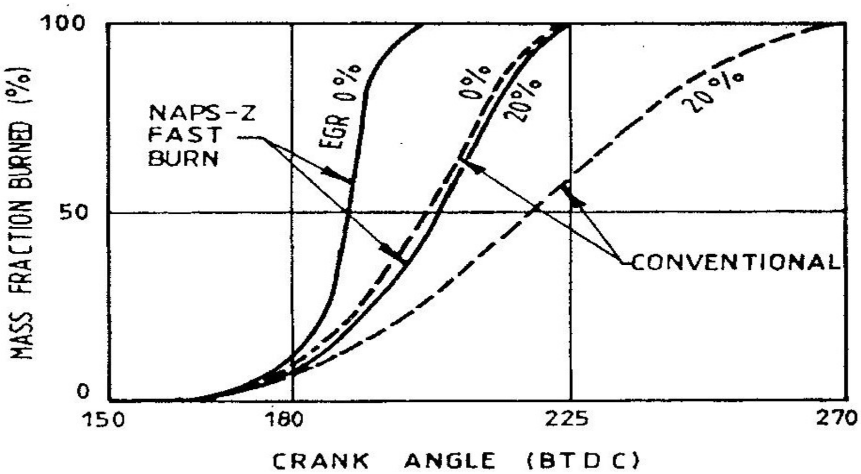


Figure 9 Fraction of the fast burn on mass burned ratio

The increase in the rate of mass fraction burned as shown in Fig. 9 is probably the result of the other changes incorporated in the Nissan NAPS-Z engine which are not employed in the conventional L-20B engine as it is evident in Table 1.

In actual fact, the NAPS-Z dual plug system masks the effect of EGR introduction through the increased probability of consistency in combustion. This is also evident from the fact that the improvement in BSFC with FAST BURN A (single plug engine, but with all the other modifications as adopted in the NAPS-Z engine, including those mentioned in Table 1) is so significant over that of the conventional engine while the gap is very narrow when the FAST BURN B (NAPS-Z) engine is compared with FAST BURN A. At zero EGR rate, the BSFCs are almost comparable in both the cases and the slight difference noticed is probably attributed to the low load conditions indicated, in which the dual plug engine is advantageous because of the reduced chances of misfire. As the EGR rate is increased, the gap in BSFCs widens due to the now-worsened ignition conditions. By having 2 points of ignition, chances are higher that at least one of the spark plug might initiate ignition, and therefore providing consistency in combustion and thus, efficiency.

From the analysis of the obtained results, one could confirm that, the noticed gains which are not due to the introduction of dual plug ignition, as declared by Harada et. al. These, in fact, have been obtained due other mechanisms incorporated in the NAPS design to improve combustion performance and reduce mechanical losses.

Table 1: Details of improvements adopted for NAPS-Z engine

Item		Concrete Measures Taken
Improved combustion performance	Improved combustion itself	Semi-spherical combustion chambers that produce good swirls
		Tangential type intake port advantageous for producing swirls
		Swirl blade to strengthen swirls
		two spark plugs per cylinder to effect fast burn combustion
	Uniform combustion among cylinders	Strengthened heating manifold using hot water for better mixture atomisation
		Tournament manifold to improved mixture distribution
		Mixture heater for better mixture atomisation
		EGR gas outlet port that assures uniform EGR distribution
Reduced mechanical loss		Use of EAI (Frictional losses are reduced through elimination of air pump)

In the work of Nakajima et. al [5], the optimisation of combustion chamber shape from wedged to hemispherical, the location of spark plugs, and the adoption of dual ignition system were the approach chosen to improve fuel economy and reduce NOx emission through the use of larger proportion of EGR.

Figs. 10 and 11 show the results obtained by Nakajima et. al. as reported in [5] where the same graphs are presented as Figs. 6 and 5 respectively. These results are commented in the report that, and I quote, " the MBT spark timing is delayed over 10 degrees, because of shortened combustion duration (with dual plug version). Fuel economy was markedly improved by fast burn and the difference becoming larger with higher EGR rate".

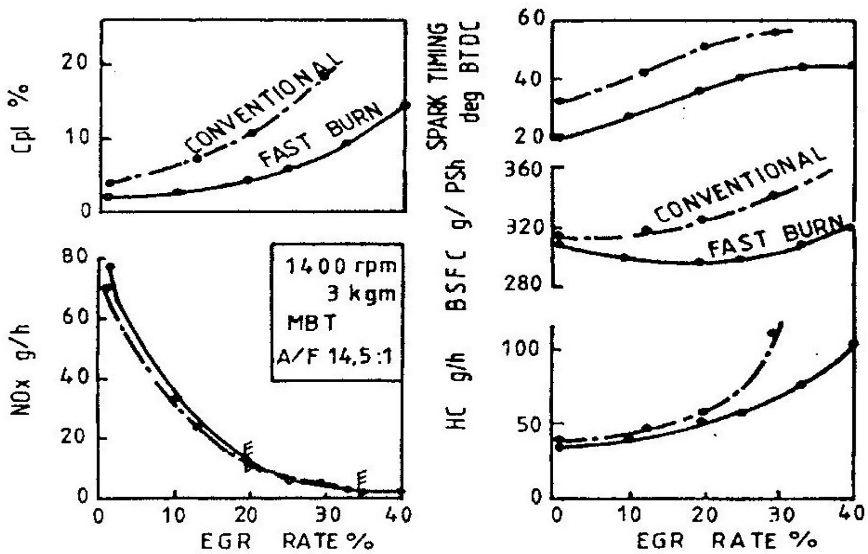


Fig. 10: Extension of EGR limit, improvement in emissions and fuel economy

The argument here is similar to that presented when discussing the work of Harada et. al that higher burning rate as noticed in Fig. 11 is not mainly attributed to the introduction of dual ignition. This should be the result of the other modifications carried on the engine, such as the optimisation of the combustion chamber, e.t.c. MBT (ignition point for best torque) advance requirement for the conventional engine does not mean in this case , shortened combustion duration with the dual plug engine, since at zero EGR no significant benefits are noticed with the dual versus single spark plugs although the MBT is retarded by more than 10 degrees throughout (Fig. 10). The significant improvements are noticed only at higher EGR rate. This, and the relative higher engine stability limit with the dual plug engine when operating with larger proportion of EGR testify the validity of the hypothesis with this engine, too.

It is evident that the dual plug system is advantageous mainly when the condition of the fuel-air mixture in the combustion chamber has deteriorated to possibly prohibit ignition and stable kernel development in most cycles. At higher EGR rates, which is one of these worsened in-cylinder conditions, the number of misfiring cycles are reduced with the dual versus single plug engines due to the increased probability of an ignitable mixture in proximity of at least one spark plug.

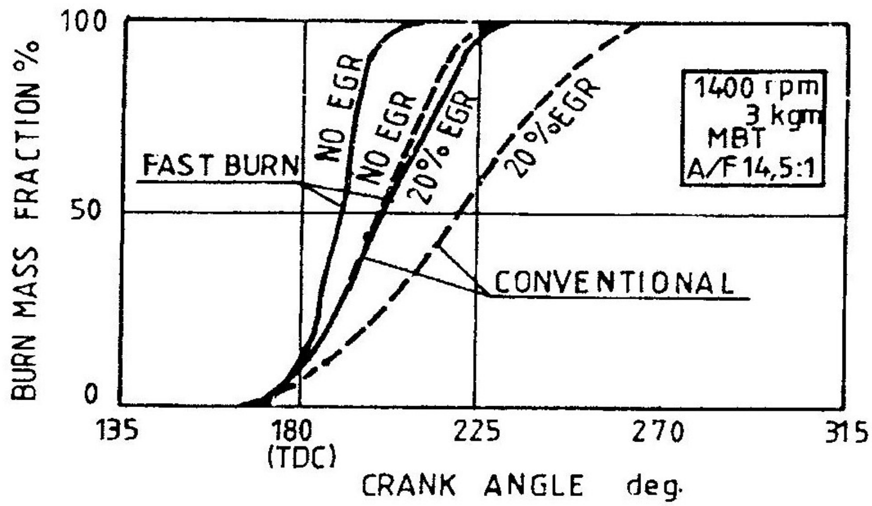


Fig. 11 Effect of fast burn on combustion duration

Quader observed in his study [6], in the section where the effect of spark location and number of spark plugs on lean combustion are described, that, and I quote "..... slight extension of lean limit appear to be possible by decreasing the flame propagating distance..........".

The above statement is supported by Figs 12 and 13 which correspond to Figs. 16 and 17 in [6] respectively.

The following observations and comments may be made as regard to the work of Quarder in relation to dual versus single plug ignitions:

In the discussed report, ignitions for all the 4 cases were timed at their respective MBT (Figs. 12 and 13). However, when the timings of the single plug systems are advanced more than the dual plug systems, it is evident that location 3 will give comparable results to the dual plug system but plug 1, due to its extreme off-centre location will still have a slower burning rate. In other words, the burning rate of te dual plug ignition engine is more or less similar to that of the single plug version if the later is properly located and ignited earlier. Two spark plugs positioned at location 3 and 4 should allow faster combustion than when located at 1 and 2 because, if spark location 3 showed shorter combustion duration than location 1, probably because of the larger flame front area, then the combination of 3 and 4 is liable to be better than that of 1 and 2.

The same could be said on the extension of lean limits. It is clearly seen from Fig. 13 that, spark location 3 has its lean limit extended compared to location 1. This is explained by the relative more central position of spark 3. Similarly, the combination of spark location 3 and 4 should therefore experience higher lean limit than spark location 1 and 2. These results once more testify the general trends of engine behaviour with dual plug ignition as stipulated in the hypothesis.

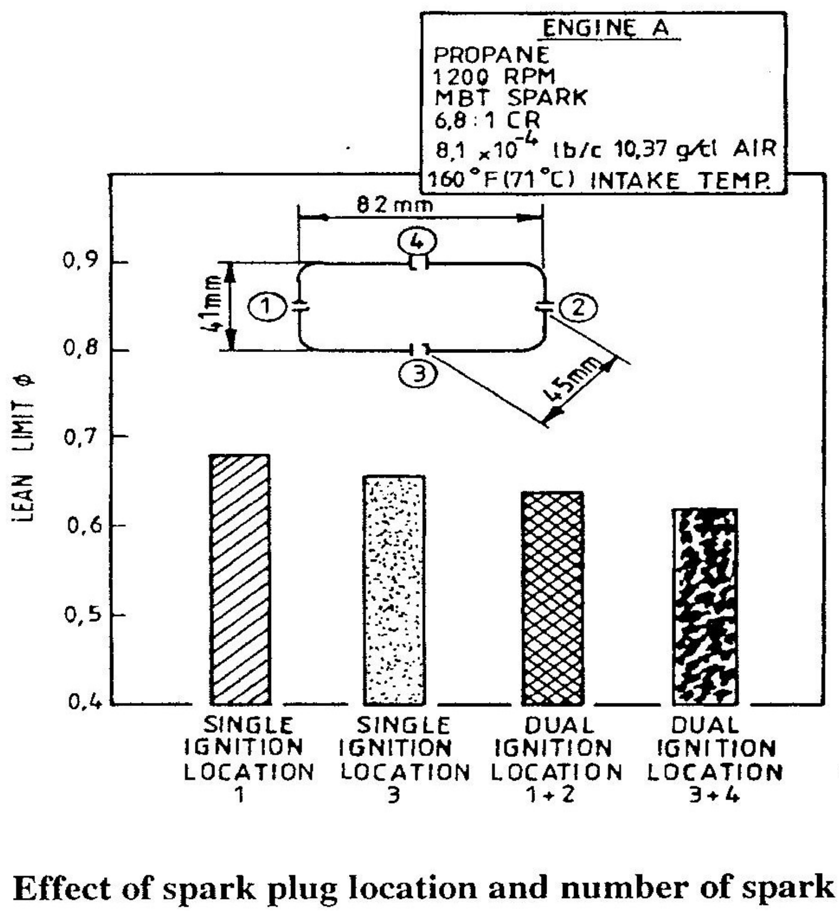


Fig. 12: Effect of spark plug location and number of spark plugs on lean limit

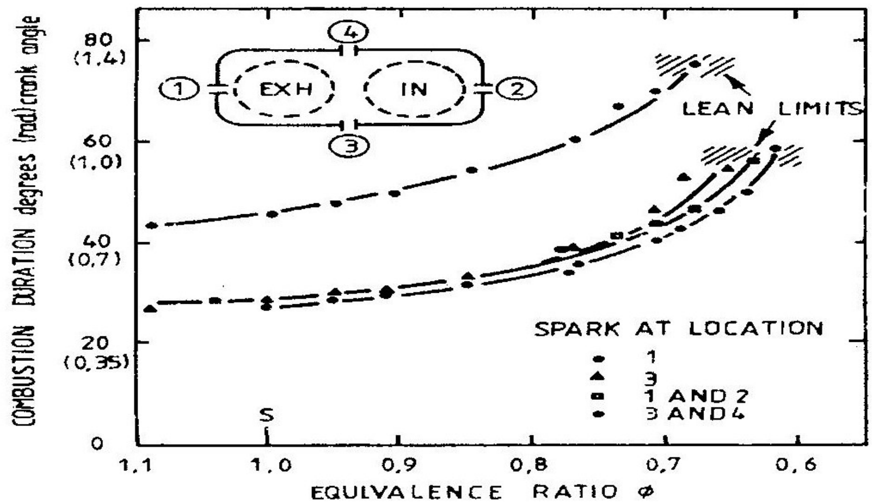


Fig.13: Effect of spark plug location and number of spark plugs on combustion duration

Figs. 14 and 15 show the effects of Air to Fuel (A/F) ratio on brake power and BSFC respectively. These results were obtained by Sinha and Gajendra Babu [7] (the above mentioned graphs are presented in Reference 7 as Figs. 5 and 6 respectively).

Sinha and Gajendra Babu attributed the above results to faster combustion. It is mentioned in their report that, and I quote, " Under leaner operating conditions, the rate of combustion increases in the case of dual ignition source as compared to the single ignition version. This results in a higher heat release rate, resulting in a higher gas pressure and temperature leading to an improvement in engine power (and BSFC)".

The author of the current paper disagrees with the above explanation. The gaps between the single and dual plugs curves of Figs. 14 and 15 are seen to widen as the fuel-air mixture is made leaner. This justify the hypothesis that dual plug engine becomes advantageous over the single spark plug version only when the condition of the charge in the combustion chamber has worsened, because in such cases ignition is more probable with the dual versus single plugs. However, such significant gains (up to 36 % increase in brake power, and 26.5 % reduction in BSFC) as reported in [7] are not expected, and especially at full load conditions. The above results may therefore be attributed to the fact that both the engines were ignited at the same time, which is not a very good idea. Because the single spark plug engine's ignition was not advanced, the dual plug version behaved as if it was ignited relatively earlier.

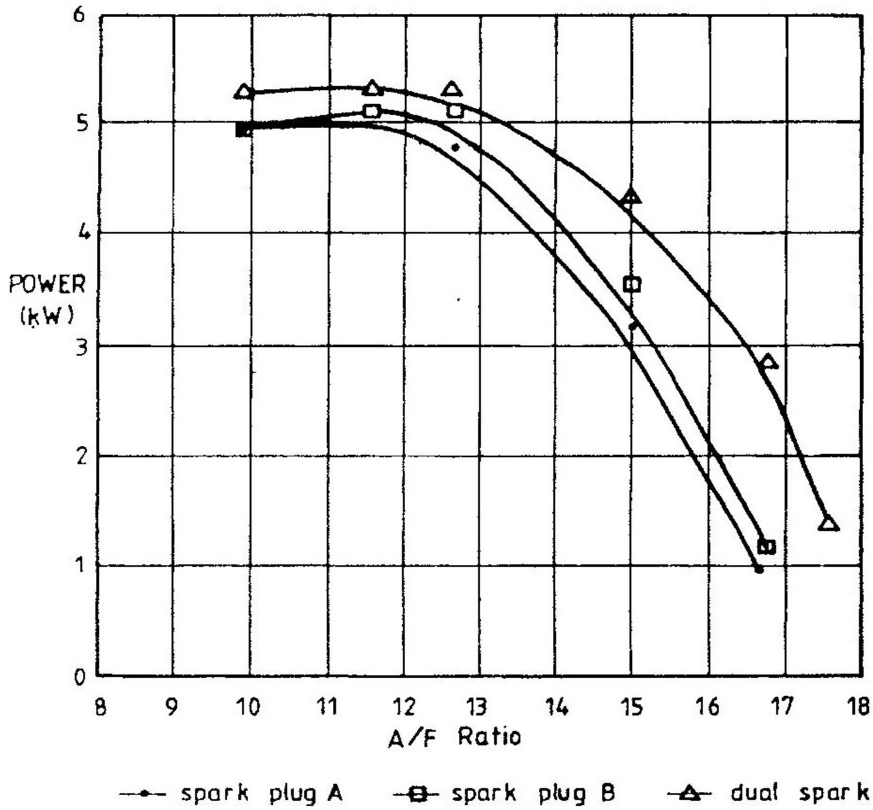


Fig. 14 Variation of power against Air Fuel (A/F) ratio

CONCLUSIONS

Different researchers have advanced different reasons for gains due to the dual spark. The reasons include faster combustion due to shorter flame travel distance, change in flame speeds and shapes, e.t.c. The opinion of the present author is that, the benefits in low pollutants emissions and fuel

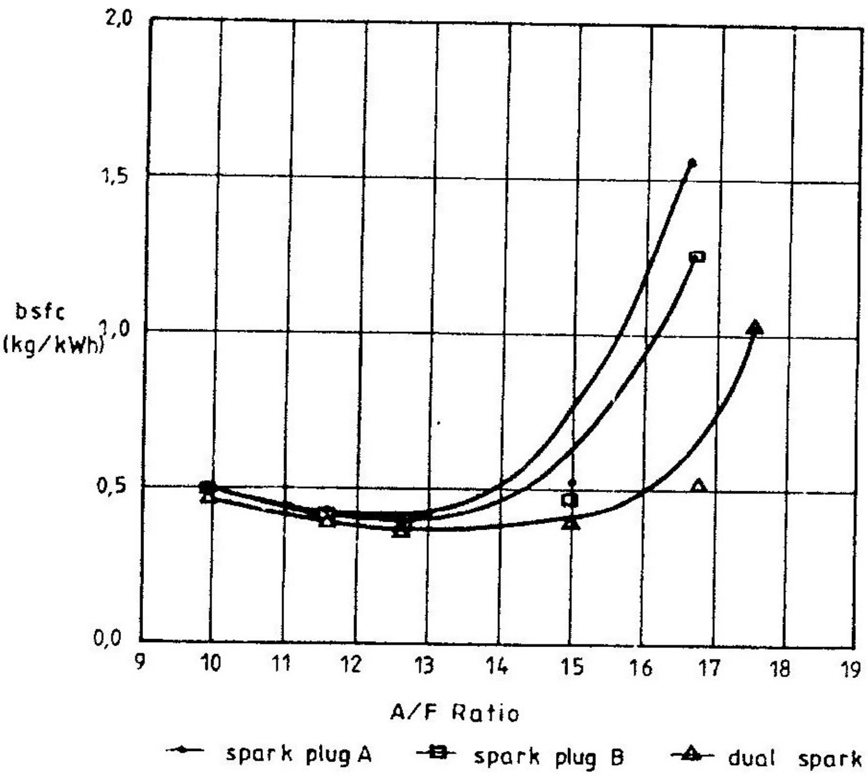


Fig. 15 Variation of BSFC versus A/F ratio

economy in an engine with dual versus single spark plugs are associated mainly with the increase in the probability of successful ignition, leading to the formation of a flame kernel. Thus, a dual plug engine is expected to give better results than a single plug one, mainly when the engine is operating with poor fuel-air mixture quality, and which are difficult to ignite. When the fuel-air mixture is in environment, conducive to flame initiation, away from misfire, viz., at full load conditions, or when operating at, or near, stoichiometric conditions, and so on, no gain is expected to be noticeable with the dual versus single plug ignition systems if the single plug engine is allowed to ignite earlier than the dual version. With the above school of thought, it has been possible to explain the published results discussed in the current paper, consistently.

More work is still required, however, to validate the hypothesis advanced in this paper. If the same will be complimented by extensive experimental work, then it could form the basis of explanation to the gains of various dual plug engines, in order to arrive at a consistent and acceptable description of the engine behaviour with dual spark plugs. In the light of that a designer can better predict when a dual ignition system will perform better than the single plug system and why.

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