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Effect of Pilot Fuel Quantity, Injector Needle Lift Pressure and Load on Combustion Characteristics of a LPG Diesel Dual Fuel Engine

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Abstract— ***In a dual fuel engine a primary fuel that is generally gaseous is mixed with air, compressed and ignited by a small pilot spray of diesel as in a diesel engine. Dual fuel engine suffers from the problems of poor brake thermal efficiency and high HC emissions, particularly at low outputs and uncontrolled combustion at higher loads. Pilot fuel quantity, injector needle lift pressure and load are important parameters controlling the combustion process in dual fuel engines. Experiments were conducted on a LPG diesel dual fuel engine at different pilot fuel quantities, injector needle lift pressure and load. Heat release patterns have been presented at low and high loads. At high outputs, the combustion of the gas by flame propagation which follows the ignition process of the pilot and the entrained gas was the dominant feature. However, at low loads, combustion of the pilot fuel and the gas entrained in it were only significant. The rapid combustion of the gaseous fuel at high output conditions particularly when the injector needle pressure was low (150 bar), resulted in rough engine operation. Results indicate a possibility of determining an optimum combination of the parameters that were investigated.***

I. INTRODUCTION

In dual fuel engines, a gaseous fuel called the primary fuel is inducted along with the intake air and is compressed like in a conventional diesel engine. This mixture does not auto-ignite due to its very high self-ignition temperature. A small amount of diesel called the pilot is injected near the end of the compression stroke to initiate the combustion of gas air mixture. The combustion of the pilot diesel leads to flame propagation in the gas-air mixture. A wide range of gaseous fuels can be easily used in dual fuel engines. Further the exhaust smoke density of dual fuel engines is much lower than for diesel engines. The Gaseous fuels cannot be used directly in conventional diesel engines even at a very high compression ratio because their self-ignition temperatures are quite high. For igniting them, we usually require some intense source of energy such as a spark or a hot glow plug or a pilot diesel injection. Spark Ignition (SI) engines experience a substantial degree of de-rating while changing over to gaseous fuels moreover have lower thermal efficiency as compared to diesel engines. Also in SI engines while using gaseous fuels spark timings needs to be controlled very closely. Using pilot diesel injection, gaseous fuels can be very conveniently used in the dual fuel mode even in existing diesel engines. Most of the advantages of Compression Ignition (CI) engines can be obtained when they work on the dual fuel mode. Further amenability of existing diesel engines to dual fueling, without any major modifications, and flexibility of dual fuel engines to switching back to pure diesel mode as and when required are two important advantages Karim (1, 2) has reported that in dual fuel engines at low loads when the gaseous fuel concentration is low, ignition delay period of the pilot fuel increases and some of the homogeneously dispersed gaseous fuel remains unburned and results in poor performance. A concentrated ignition source is needed for the combustion of the inducted fuel at low loads. Further, injection timing of the pilot fuel, injector opening pressure, pilot fuel quantity and engine load are some of the important variables controlling the performance of dual fuel engines at light loads. Poor combustion of the gaseous fuel at low loads because of the dilute fuel air mixtures results in high carbon monoxide and unburned hydrocarbon emissions. Any measure that lowers the effective lean flammability limit of the charge and promotes flame propagation will improve the part load performance. Omi Nwafor (3) conducted series of experiments on a natural gas fumigated diesel engine and some quantity of pilot diesel fuel was injected for the purpose of initiating combustion. The ignition delay of the dual-fuel engine increases with decrease in engine speed, in contrast to pure diesel fuel operation. The cylinder pressure crank angle and heat release diagrams indicate that dual-fuel operations exhibit longer ignition delay and slower burning rates. Maximum peak cylinder pressure is reduced and the initial rate of pressure rise is low compared to diesel fuel operation. The power output of the dual-fuel operation is less compared to diesel fuel test results. In dual-fuel engines, three types of knock were identified. There are diesel knock due to combustion of premixed pilot fuel, spark knock due to autoignition of end gas, and erratic knock due to secondary ignition of the alternative fuel. The main factors that influence the occurrence of these knock are the pilot quantity, delay period, load, speed, and gas flow rate and time interval for secondary ignition. Increasing the pilot fuel and reducing primary fuel reduces the knocking phenomena in dual-fuel engines. Ahmad et al. (4) showed that Dual-fuel engines generally suffer from the problem of lower peak brake power and lower peak engine cylinder pressure due to lower volumetric efficiency; although an improvement in brake specific energy consumption is observed compared to pure diesel mode Bilcan et al. (5) explained that the dual fuel engines can use a wide variety of gaseous fuels efficiently while emitting lesser smoke and particulate than their diesel counterparts. In these engines, a primary gaseous fuel, like biogas, producer gas, LPG etc. supplies the major share of the input energy. They developed model which can be used with good agreement to predict the rate of heat release rate in a dual fuel engine running at constant load and with variable diesel substitution. A fairly good agreement was observed between the simulation and the experimental results. Ehsan and Shafiquzzaman(6) in there analysis of three probable high-load dual fuel operations revealed that running the engine at nearly 90% of the load capacity with 88% diesel replacement by natural gas would give the highest overall economic benefit. Lakshmanan (7) found that there is an appreciable reduction in smoke level in dual fuel mode as compared to diesel mode. It dropped from 7 to 6.50 BSU when compared to neat diesel operation. A perceivable reduction in HC, CO and CO2 emissions was observed with acetylene operated dual fuel mode. The reduction in HC and CO2 emissions at maximum load is of 8 % and 3% respectively when compared to diesel operation. Luijten et al. (8) in their study of Jatropha oil with biogas in a dual fuel CI engine has concluded that for lower loads, thermal efficiency decreases, down to 22% at the highest biogas substitution. Elnajjar (9) confirms that increasing the amount of pilot fuel mass reduces the engine combustion problems and overall engine noise. To improve performance and exhaust emissions of a converted dual-fuel natural-gas engine, the effects of basic parameters were experimentally investigated by Ishiyama et. al. (10). The results show that a small amount of pilot fuel with a moderate injection rate is effective for suppressing knock at high loads. Adequate control of pilot fuel amount, injection timing gives diesel- equivalent thermal efficiency with very low smoke emission over a wide range of loads The effects of changes in the cetane number of diesel liquid pilot fuels on the ignition delay period in dual fuel engines were investigated experimentally by Gunea et al. (11) using different pilot fuels. The ignition delay variation with increased gaseous fuel admission showed a strong dependence on both the quantity and quality of the pilot fuel used. It was found that the use of high cetane number pilot liquid fuels permitted smaller pilot quantities to be used satisfactorily. Papagiannakis (12) obtained longer duration of combustion especially at low and intermediate supplement ratios of diesel gaseous fuels. At high load, duration of combustion increases when increasing the concentration of the gaseous fuel but at high supplement ratios, it provides converge to the respective one observed under normal diesel operation. Rao et al.(13) and many other has found in their studies that the engine operation is more economical on the pure diesel mode at lower loads, however at higher loads dual-fuel operation is better smoother and more efficient. At lower loads, mechanical, brake thermal efficiencies of the engine are more on the pure diesel mode but at higher loads the reverse is true Vijayabalan et al. (14) used the glow plug assisted dual fuel operation to improve the combustion. It shows higher peak heat release rate compared to dual fuel operation. The peak pressures are higher in glow plug assisted dual fuel operation in the entire load range when compared to dual fuel operation without glow plug. In general glow plug assistance improves the part load performance in dual fuel engine with a significant reduction in emissions.

II. APPARATUS AND EXPERIMENTAL PROCEDURE

The schematic layout of the test setup used is indicated in Fig. 1. A single cylinder, direct injection, water cooled diesel engine was used for this experimental work. The specifications of the engine are given in Appendix –A

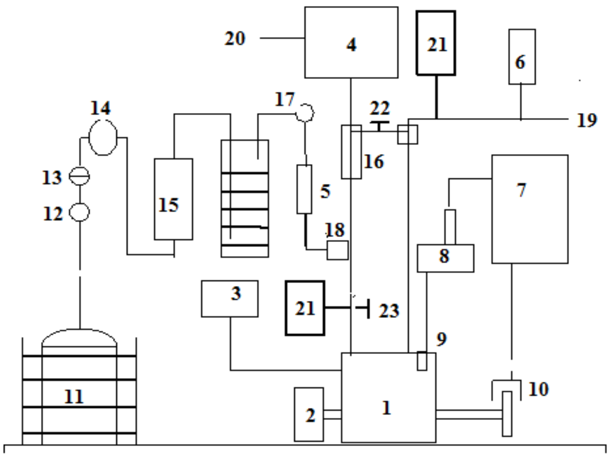

Fig 1 Experimental Set up

1-Engine, 2-Dynamometer, 3-Diesel tank and Measurement system, 4-Air flow Surge tank and Meter, 5-Air Pre Heater, 6-HC/CO Analyzer, 7-PC Based Data Acquisition system, 8-Charge Amplifier, 9-Pressure Pickup, 10-Shaft Position Encoder, 11-LPG cylinder in a Constant Temperature water Bath, 12-Control valve, 13-Pressure Regulator, 14-Positive Displacement Gas Flow Meter, 15-Rotometer, 16-Flame Trap, 17-Control Valve, 18-Gas Mixer, 19-Exhaust Outlet, 20-Air Inlet, 21-Temperature and Pressure Measurement Points, 22-EGR Valve, 23-Throttle Valve .

An LPG connection was made on the intake manifold. Governor varied pilot diesel flow while LPG flow rate was varied manually. Cylinder pressure signals obtained from a flush mounted quartz pressure pickup were recorded on a personal computer. The heat release rate and other

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combustion parameters were computed using software developed for the purpose after obtaining the average pressure signal from 100 engine cycles. Based on a previous experimental program injection timing of 27.4º BTDC and 24º BTDC were selected for dual fuel and diesel operation respectively. Based on the same work injection pressure of 150 bar in dual fuel operation was used.

III. RESULTS AND DISCUSSION

A. Effect of Pilot Fuel Quantity on Heat Release

Fig. 2 shows the effect of pilot fuel quantity (4.6, 8.4 mg/cycle) on heat release rate and mass fraction burnt at 20 % of full load. The results with neat diesel operation are also given for comparison. The intake temperature was maintained at 70° C. The heat release during the first phase, which is mainly due to combustion of pilot diesel decreases substantially with decreased pilot fuel quantity. Thus with decreasing pilot, the source of ignition for the gas-air mixture becomes weak, adversely affecting the subsequent combustion process resulting in lower brake thermal efficiency. A decrease in pilot fuel quantity at this load and temperature, leads to an increase in ignition delay. This will lead to increased dispersion of injected pilot before its ignition which further weakens the ignition of the gas air mixture. Also the occurrence of maximum heat release is delayed with decreasing pilot fuel quantity at light loads and high gas substitutions e.g. low pilots. It is seen in the Fig. 2, that as compared to straight diesel operation, the peak heat release rate decreases in the dual fuel mode. The peak heat release rate decreases with decrease in pilot fuel quantity. This can be explained by the fact that with decreasing pilot, the amount of fuel prepared for burning during delay period also decreases and hence lesser heat is released during this stage. It also suggests that the contribution of the gaseous fuel to heat release during this stage is not significant as in all cases of dual fuel operation, the peak of heat release is less than that for straight diesel. This behavior is observed only at light loads (lean gas-air mixtures). The same trend is confirmed by mass fraction burnt curve as seen in Fig. 3. In the second stage of combustion due to diffusive burning of the diesel pilot left after the first stage and simultaneous combustion of gaseous fuel, cumulative heat release is slightly higher as-compared to straight diesel. With larger pilot (8.4 mg/cycle), the combustion of the gaseous fuel is better leading to higher mass fraction burnt and higher brake thermal efficiency in dual fuel mode as compared to the corresponding diesel operation Figs 4 & 5 shows the rate of heat release and mass fraction burnt at 80% of full load, with 10.7, 5.9 and 3.6 mg/cycle pilot fuel (in which LPG accounts for about 40, 65 and 86% of the total heat input respectively). The intake temperature has been maintained at the optimum of 60° C. It is seen that with the pilot fuel quantity of 10.7 and 5.9 mg/ cycle, three phases of combustion are present. The three peaks in the three phases are very clear at the pilot of 10.7 mg/cycle. In the first stage of combustion the heat is mainly released due to premixed burning of part or whole of the pilot quantity in addition small part of gas entrained in the spray. In the second stage by auto-ignition of gas air mixture in the close vicinity of pilot spray and diffusive burning of the remaining pilot fuel whereas in the third stage heat is released due to burning of gas air mixture by flame propagation initiated from spray zone are responsible for heat release. With 3.6 mg/cycle pilot it is difficult to differentiate between second and third phase. It is also clear that with 10.7 mg/cycle pilot the heat release rate in first phase of combustion is responsible for high rate of pressure rise which sometimes are heard as audible knock. Whereas, with 5.9 mg/cycle pilot, both the combustion of the remaining pilot fuel and gaseous fuel nearby spray (e.g. second phase of combustion) is responsible for high rate of pressure rise. In the case of 3.36 mg/cycle pilot the rate of pressure rise is quite low.

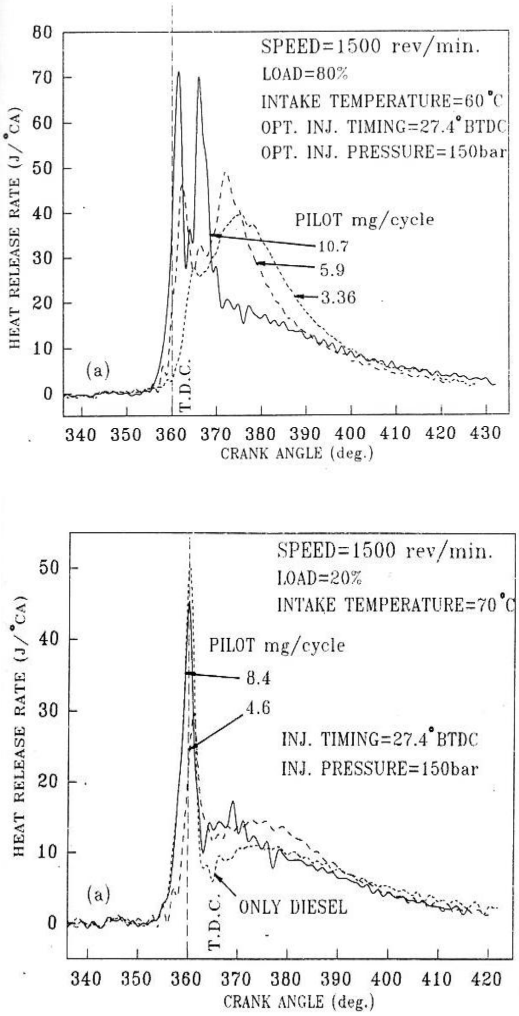

Fig 2 Effect of Pilot Fuel Quantity on Heat Release Rate & Fig 3 Effect of Pilot Fuel Quantity on Mass Fraction Burnt

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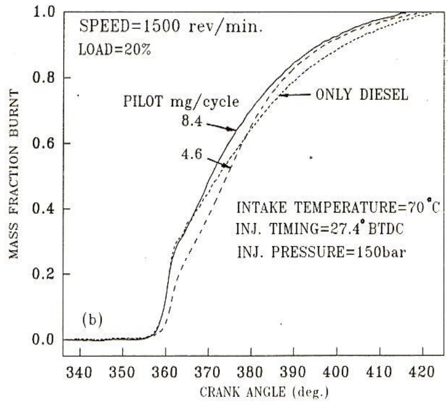

Fig 4 Effect of Pilot Fuel Quantity on Heat Release Rate

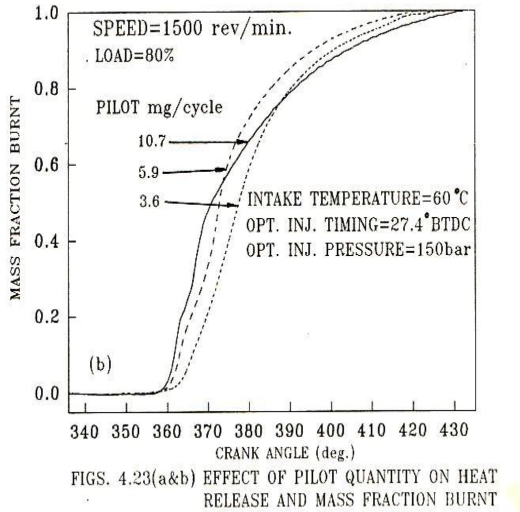

Fig 5 Effect of Pilot Fuel Quantity on Mass Fraction Burnt

It can also be concluded that with higher pilot fuel the knocking occurs mainly because of 'auto- ignition' of the diesel and gaseous fuel nearby pilot spray. The 'end-gas' type of knock as found in normal S. I. engines has not been observed during present investigations with LPG. Probably, because LPG has a high octane rating, end gas knock has not been observed even at high intake temperatures, and very low pilots. To avoid knock, which occurs at high outputs in dual fuel engines, low pilot fuel quantities and low intake temperatures are better. At higher loads the combustion duration was longest with the highest pilot namely 10.7 mg/cycle as compared to lower pilot fuels as seen in the Fig. 5 due to relatively slow diffusive burning of the pilot diesel in the later part of the combustion process. Maximum brake thermal efficiency was obtained with 5.9 mg/cycle pilot fuel.

B. Effect of Load on Heat Release

To study the effect of engine output on heat release rate and mass fraction burnt, an intake temperature (34^0 C) and pilot fuel quantity (8.4 mg/cycle) was selected as these parameters were studied at every load. The load was varied from 20% to 100% of full load as indicated in Fig. 6 & 7.

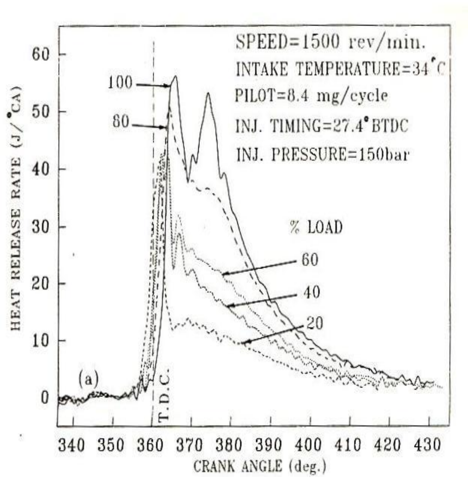

Fig 6 Effect of Load on Heat Release Rate

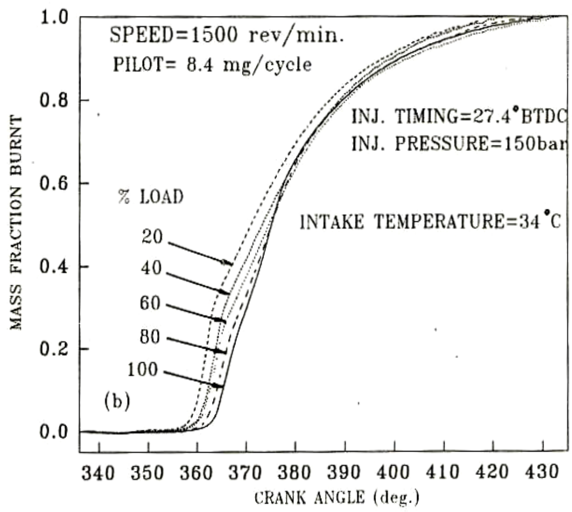

Fig 7 Effect of Load on Mass Fraction Burnt

At constant pilot, as the load increases the start of combustion gets retarded. At constant pilot as the output increases the gas quantity supplied per cycle increases. As mentioned earlier, the presence of the gas at the time of injection of the pilot fuel increases the ignition delay of the pilot fuel. Hence as load increases, it is seen from Figs. 6 & 7 that the ignition delay period increases. The difference in starting point of combustion was observed to be 7^0 CA between 20 % and 100 % load. The combustion duration was also observed to be longer at higher loads as compared to lower loads. The rate of heat release in second phase of combustion starts to dominate as load increases and it reached as high as 57 $J/^0$ crank angle at 100% load as compared to 30 $J/^0$ CA at *20%* load. The delayed combustion at higher loads is clearly visible in mass fraction burnt curves as shown in Fig. 7

C. Effect of Injector Opening Pressure on Heat Release

As mentioned earlier, at 100% load the injection pressure had to be raised from 150 bar to 200 bar for knock free operation. The brake thermal efficiency was also observed to be higher at 200 bar. As shown in Fig. 8, with 200 bar injector opening pressure combustion starts late

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(approximately 50˚ CA) as compared to 150 bar pressure. The high injection pressure affects good atomization, vaporization and dispersion of the liquid pilot fuel. It is clearly observed from the heat release rate diagram that with same pilot fuel quantity, due to greater dispersion of pilot fuel, the rate of heat release in first phase of combustion is less with 200 bar injector opening pressure. The peak rate of heat release in the second phase is also approximately half of that developed with 150 bar injection pressure. At higher loads, this second stage is responsible for knock. It is also clearly visible in pressure crank angle diagrams that peak pressure in the cycle is at the same crank angle where heat release in second stage is maximum, Lower rate of heat release with 200 bar injection pressure in this stage as compared to 150 bar pressure is the main reason for very smooth running of engine with 200 bar injector opening pressure. Due to larger number of nuclei available for combustion of homogeneous mixture, the transition from second to third phase of combustion is quite smooth. Further higher injection pressure also resulted in shorter combustion duration and high thermal efficiency with very smooth engine operation. Use of a high injection pressure at very high loads seems to be a good remedy to decrease engine knock in dual fuel engines.

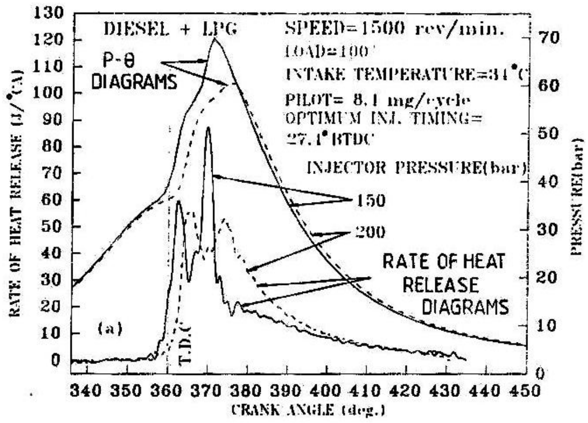

Fig 8 Effect of Injection Pressure on Heat Release Rate

However, it is observed that vapor lock and injector needle cooling problem is severe with higher injection pressure. Mass fraction burnt curves using injector opening pressure of 150 and 200 bar are also shown in Fig. 9.

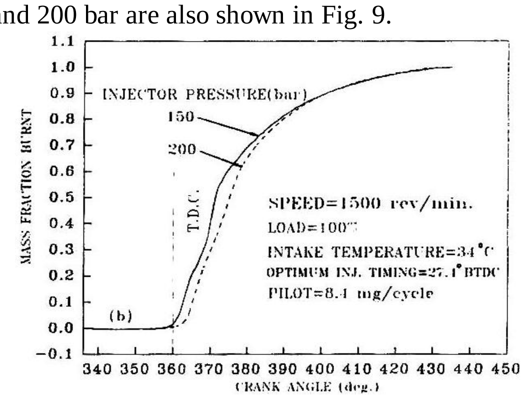

Fig 9 Effect of Injection Pressure on Mass Fraction Burnt

IV. SUMMARY/CONCLUSIONS

Following salient conclusions have been drawn on the basis of present experimental investigations;

1. In dual fuel engines, three stages of combustion at higher loads and two stages at lower loads are observed.
2. In the first stage of combustion the heat is mainly released due to premixed burning of part or whole of the pilot quantity in addition small part of gas entrained in the spray. In the second stage by auto-ignition of gas air mixture in the close vicinity of pilot spray and diffusive burning of the remaining pilot fuel whereas in the third stage heat is released due to burning of gas air mixture by flame propagation initiated from spray zone are responsible for heat release.
3. As compared to straight diesel operation, the peak heat release rate decreases in the dual fuel mode.
4. It can also be concluded that with higher pilot fuel the knocking occurs mainly because of 'auto- ignition' of the diesel and gaseous fuel nearby pilot spray. The 'end-gas' type of knock as found in normal S. I. engines has not been observed during present investigations with LPG.
5. The combustion duration was also observed to be longer at higher loads as compared to lower loads.

Use of a high injection pressure at very high loads seems to be a good remedy to decrease engine knock in dual fuel engines.

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