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Cylinder Pressure Analysis of a Diesel Engine Using Oxygen-Enriched Air and Emulsified Fuels

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ABSTRACT

Analytical studies of oxygen-enriched diesel engine combustion have indicated the various benefits as well as the need for using cheaper fuels with water addition. To verify analytical results, a series of single-cylinder diesel engine tests were conducted to investigate the concepts of oxygen enriched air (OEA) for combustion with water emulsified fuels. Cylinder pressure traces were obtained for inlet oxygen levels of 21% to 35% and fuel emulsions with water contents of 0% to 20%. Data for emulsified fuels included no. 2 and no. 4 diesel fuels. The excess oxygen for the tests was supplied from compressed bottled oxygen connected to the intake manifold. The cylinder pressure data was collected with an AVL pressure transducer and a personal computer-based data logging system. The crank angle was measured with an optical encoder. In each data run, 30 consecutive cycles were recorded and later averaged for analysis. The data analysis was done with a heat release analysis code written for a personal computer.

The results indicate that water emulsified fuels consistently gave a slight improvement in thermal efficiency and a greater portion of the fuel energy was released in the early part of the combustion process compared with base fuels. OEA reduced the ignition delay and measurably changed the shape of the calculated heat release rate and cumulative heat release diagrams. Comparative cylinder gas temperatures, computed from measured cylinder pressures, are presented in an effort to explain changes observed in the emissions of nitrogen oxides (NO_x), smoke, and particulate matters. The data indicates that smoke and particulate emissions decrease and NO_x increases when intake O_2 level is increased. A future test program to optimize the engine design and operating variables, including inlet oxygen level and water level in the fuel emulsion, would result in the realization of the full potential of these concepts.

INTRODUCTION

Reciprocating engines using oxygen-enriched combustion air have several advantages such as increased power density, reduced smoke, hydrocarbon (HC) and particulate emissions and the ability to use cheaper, less-refined fuels. Although these benefits have been demonstrated by several researchers (1,2,3,4,5,6),* increase in NOx emissions and the lack of an economical

* Numbers in parentheses designate references cited at end of paper.

on-line oxygen-enrichment device have prevented any application of this concept. Recent progress in the development of oxygen-enrichment devices, such as "asymmetric hollow polymeric" membranes, and tough emissions standards have stimulated renewed interest in this concept, specifically in diesel engine applications (7,8,9). The research efforts by Argonne National Laboratory (ANL) have included tests of a single-cylinder diesel engine with oxygen-enriched air and diesel fuels and their emulsions. The results of these tests are being reported in three publications. This paper considers the measured cylinder pressure data and analysis when oxygen levels in the intake varied from 21% to 35% by volume. Two different diesel fuels, no. 2 and no. 4 and their emulsions with water were tested. Water content levels of 0%, 5%, and 10% by fuel weight were included in the test matrix. However, operating difficulties were encountered in maintaining the stability of the emulsions, especially with no. 2 diesel fuel. As a result, the data with emulsified fuels varied widely, up to 22%, in water content. The comparisons of the steady-state parameters, such as power output levels, NO_x and particulate emissions, and thermal efficiency, were recently published by ANL (10). Since the effects of oxygen concentration on ignition delay, cylinder pressures, and on the rates of pressure rise and heat release are important in understanding diesel combustion in oxygen-enriched conditions, the present investigation includes combustion with emulsified fuels in an oxygen-enriched environment.

EXPERIMENTAL SETUP

ENGINE AND FUELS USED - A single-cylinder, four-stroke, direct-injection diesel engine was used in this series of experiments. This engine is a one cylinder version of a heavy-duty diesel engine commonly used in highway trucks and other applications. The major specifications of the base engine are given in Table 1. No hardware changes were made to the basic engine, and the manufacturer's recommendations were used in the setup and operating procedures.

Table 1 Test Engine Specifications

Item	Specifications
Number of Cylinders	1
Bore x Stroke (mm)	137 x 165
Displacement (l)	2.44
Engine Speed (rpm)	1800
Injection Timing (btdc)	33^{o}
Compression Ratio	14.5
Peak Cylinder Pressure (MPa)	11.3

The engine was designed to run on no. 2 diesel fuel. The objective of this series of tests was to run the engine on a less- refined fuel, such as no. 6 diesel. However it was felt that the engine might not run smoothly on no. 6 diesel fuel without extensive modifications. Hence, as a compromise, the engine was tested with no. 4 fuel, which is generally used in marine applications. Water was introducted into the combustion process by emulsifying the two base fuels with distilled water and a small percentage of emulsifying chemical additive (amine alkyl benzene sulfonate). Three levels of water content were tested with each base fuel. The fuel specifications are listed in Table 2. The oxygen supply, the test fuel preparation systems, and the general test cell instrumentation are discussed in a previous publication (10). Cylinder pressure measurements, the subject of this paper, were made by using an AVL piezoelectric transducer located at the cylinder head combustion surface. Top dead center and crank angle markings were referenced by an optical rotary shaft encoder attached to the front of the crankshaft. The cylinder pressure and the crank angle signals were processed through an IBM PC/AT computer. The individual cycles and a 30-cycle average pressure diagram were recorded on a floppy disk

Table 2 Fuel Specifications

Item	no. 2 diesel	no. 4 diesel
Kinematic viscosity (Cs @ 80°C)	1.8	5.2
Lower heating value (kJ/kg)	42,668	40,909
Water used for emulsion (% of fuel weight)	0, 5, 10	0, 5, 10
Chemical additive (%)	0.333	1.0

for each engine test condition. A simplified heat release computer code was written for a PC to analyze the pressure. More complete details of the data collection and heat release analysis methodology are available from ref. 11.

TEST MATRIX - Two engine operating conditions were tested in this series. "Fifty-percent load" is defined as the engine operating conditions (intake manifold pressure, exhaust manifold pressure, and mass flow rate of air and oxygen) corresponding to 50% brake power level of the base engine, which is 18.65 kW (25 hp). "One-hundred-percent load" is defined as the engine operating conditions corresponding to the rated power level of the base engine, which is 37.3 kW (50 hp). The intake manifold pressures were maintained at 112 cm Hg abs. at "50% load" and 140 cm Hg abs. at "100% load." The exhaust manifold pressure was maintained at 81 cm Hg abs. throughout the test. Three types of data were obtained at each oxygen level:

1. Constant power output,
2. Constant exhaust to intake- oxygen-ratio, and
3. Constant exhaust oxygen level

The intake oxygen level was varied from 21% to 35%. Water content of the fuel emulsion ranged from 0% to 22%. A total of 112 test runs were made, and several of graphs were plotted. Only a portion of the most significant trend curves are presented in this paper. Baseline data were collected frequently during the test series. Although some data had to be disregarded due to instrumentation failures, the test series was completed without any major engine problems.

DISCUSSION

The effects of oxygen enrichment and emulsification of fuels on engine power density, thermal efficiency, and exhaust emissions have been published (10). In this paper, ignition delay, cylinder pressure levels and rates, of pressure rise, apparent heat release rates, and calculated combustion temperatures are discussed. For each of these parameters, the effects of intake oxygen level, weight fraction of water in the fuel, type of base fuel (i.e. no. 2 or no. 4 diesel fuel) and the power output levels are reported.

IGNITION DELAY - Ignition delay is the interval between the fuel injection into the cylinder and the start of energy release due to combustion. Previous research has indicated that oxygen enrichment would reduce ignition delay (5,8). Figure 1 illustrates the effect of power output level and intake oxygen level on ignition delay. An ignition delay reduction of 4 degree crank angle was observed when the intake O_2 level was increased to 35% from 25%. The figure also shows that as the engine power output was increased, the ignition delay was reduced. This ignition delay reduction is important because it allows the injection timing to be retarded without degrading combustion. Retarding the injection timing is a commonly used method of NO_x reduction in diesel engines. Because oxygen enrichment has been demonstrated to increase NO_x production (4, 10), a means to control NO_x is needed. In this project, water (in the form of emulsified fuel) was introduced in the combustion process. The presence of water tends to increase the ignition delay. Figure 2 shows the experimental ignition delay when the amount of water in the fuel was changed. It is clear that a combination of a small amount of water in the fuel and oxygen-enriched air for combustion results in a net reduction in ignition delay of three to four crank angle degrees. Figure 3 shows a comparison of the ignition delays when the base was changed from no. 2 to no. 4 diesel fuel. The less-refined no. 4 fuel consistently had higher ignition delay, which indicates the need for developing a combustion system specifically for low-grade fuels.

CYLINDER PRESSURES - Higher oxygen levels and power levels increase peak cylinder pressures, as shown in Fig. 4. However, the magnitude of the increase in peak pressure is less than 15%. Water in the fuel tends to reduce the peak pressures, and low-grade fuel tends to increase the peak pressures, as shown in Fig. 5. The 30-cycle average cylinder pressure diagram was smoothed by progressively averaging three points before and three points after each crank angle. Figure 6 illustrates the difference in the pressure diagrams due to intake oxygen level. Since the differences are not too big, only the two extreme oxygen levels (21% and 35%) are shown. Figure 7 shows the rates of pressure rise, dp/d,θ for 21% and 35% oxygen levels in an expanded scale for the beginning part of combustion. The rate of pressure rise due to combustion is higher at a higher O_2 level, which indicates faster burning of fuel. The combined effects of water in the fuel, oxygen-enriched air, and increased power level on the cylinder pressure diagram are illustrated in Fig. 8. In this figure, run 37 is the base case, whereas run 100 is the data for the 35% oxygen, 6.9% water in the fuel, and the increased power condition. It is clear that there is a net increase in dp/d as well as a 17% increase in peak pressure. However, the cylinder pressure levels are within current diesel engine design limits. Figure 9 compares the cylinder pressure traces and Fig. 10 compares the rate of pressure rise for no. 2 and no. 4 fuels. The peak pressure with no. 4 fuel is slightly higher to produce the same power as no. 2 fuel. The data also indicated a later start of combustion and a higher rate of pressure rise with no. 4 fuel.

HEAT RELEASE RATES - From the experimental cylinder pressure diagrams, apparent rates of heat release were calculated. The purpose was to identify overall trends and effects on combustion due to intake oxygen level, amount of water in the fuel-water emulsion, and the power output. It is recognized that the engine combustion chamber was designed and fine-tuned for standard no. 2 diesel fuel and 21% oxygen in the intake air. For other fuels, emulsions, and oxygen levels, combustion chamber design must be specifically optimized to achieve the potential performance of the engine. The heat release comparisons presented here could be used as a starting point for more detailed combustion studies and engine development incorporating these technologies. Figure 11 presents the cumulative rate of burning for the same cases discussed earlier. The significant trend is that more of the energy release occurs in the earlier part of the combustion cycle when higher oxygen level is available than in the latter part of the cycle. The ignition delay changes discussed earlier are evident in Fig. 11. The effects of water content in the fuel on heat release rate are shown in Fig. 12. When water is present in the fuel, the combustion starts a little later, but the rate of burning is measurably higher in the early part of combustion. This might be due to "micro explosion" phenomenon proposed by other investigators (12). Figure 13 compares the cumulative heat release diagrams of no. 2 and no. 4 diesel fuels.

COMBUSTION TEMPERATURES - As part of the heat release analysis, combustion gas temperatures are calculated at each crank angle. The gas temperature is a critical rate controlling factor in NO_x formation. The comparisons presented here are meant to provide relative effects of oxygen and water levels on the combustion temperatures, which, in turn, would provide some clues to the effects on NO_x formation. Figures 14 and 15 compare the effects of intake oxygen level and water content of the fuel on the calculated gas temperatures. When the oxygen level is increased to 35%, the peak gas temperature increases by about 27%. In addition, the rate of temperature rise is significantly higher. This explains the increase in NO_x emissions. The effect of introducing water into the combustion process in the form of emulsified fuel reduces the gas temperature and the rate of temperature rise, which lead to lower NO_x emissions.

CONCLUSIONS AND RECOMMENDATIONS

In this typical heavy-duty diesel engine, oxygen-enriched combustion air reduces the ignition delay in diesel engines by 3-6 degrees crank angle at 1800 rpm. The use of emulsified fuel with a water content of up to approximately 7% slightly increases the ignition delay (by about one-half degree crank angle). The ignition delay is further reduced when the engine power output is increased at higher oxygen levels. This fact indicates that the injection timing could be retarded by six degrees which would reduce NO_x emissions, without adversely effecting combustion. ANL is planning to obtain test data at different injection timings in the next phase of the project. The no. 4 fuel has higher ignition delay compared with the no. 2 fuel. Oxygen enrichment (from 21 to 35%) increases peak cylinder pressures by about 15%. Water in the fuel up to about 7% reduces the peak pressures by 2-3%. The use of no. 4 fuel slightly increases the peak pressures. The cylinder pressure diagrams indicate that oxygen enrichment increases the rate of pressure rise and this trend persists when emulsified fuels are used. However, the use of no.4 fuel did not significantly affect the overall cylinder pressure diagram.

Oxygen enrichment results in a significantly higher proportion of energy release in the early part of the combustion process. This factor should be taken into consideration when combustion system optimization efforts are undertaken to incorporate oxygen enrichment technology in diesel engine applications. The effects of oxygen enrichment and water in the fuel on gas temperatures are as expected. A research effort to correlate the changes in combustion temperatures to oxygen level in the air and water level in the fuel on one side and to measured NO_x emissions on the other side will be useful in devising NOx control measures. A detailed study of fundamentals of engine combustion should be undertaken to correlate the data obtained in this project.

ACKNOWLEDGMENT

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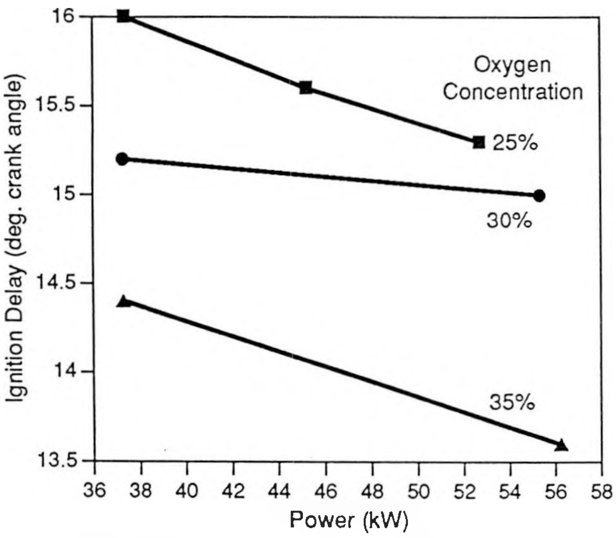

Fig. 1 Effect of power output and oxygen level on ignition delay (no. 2 diesel fuel, 100% load, no water; baseline ignition delay=19 deg.)

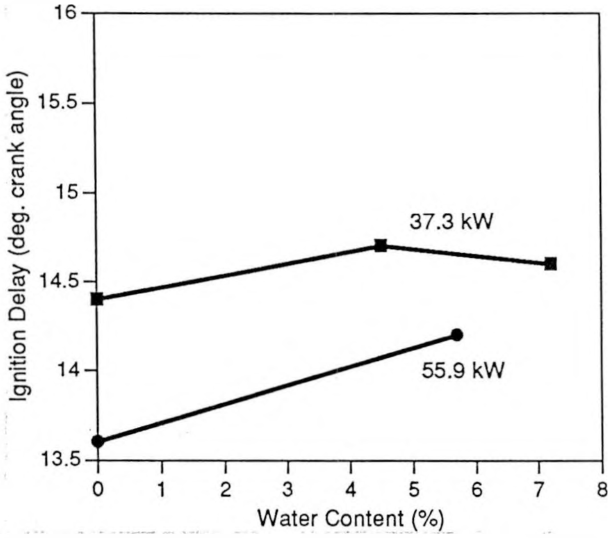

Fig. 2 Effect of water content in the fuel and power output on ignition delay (no. 2 diesel fuel, 100% load, 35% O_2; base engine ignition delay=19 deg.)

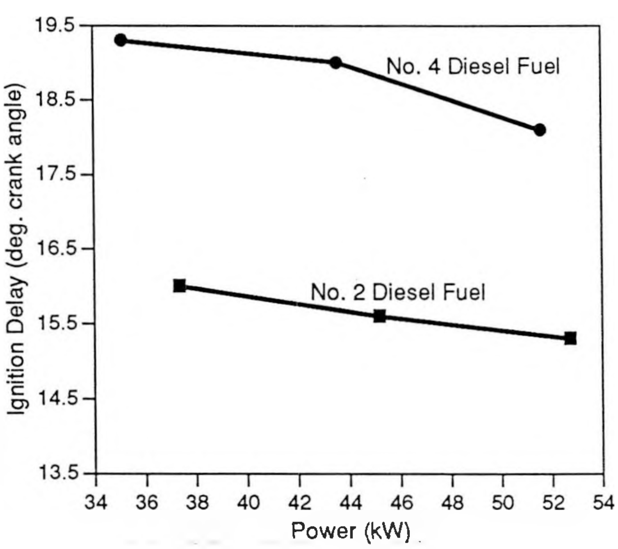

Fig. 3 Effects of using less-refined fuel on ignition delay (100% load, no water 25% O_2)

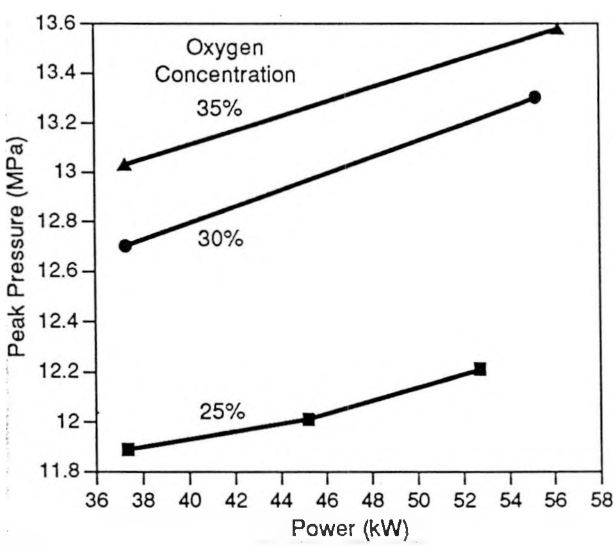

Fig. 4 Effects of power output and oxygen level on peak cylinder pressure (no. 2 diesel fuel, 100% load, no water; base engine peak pressure=11.3 MPa)

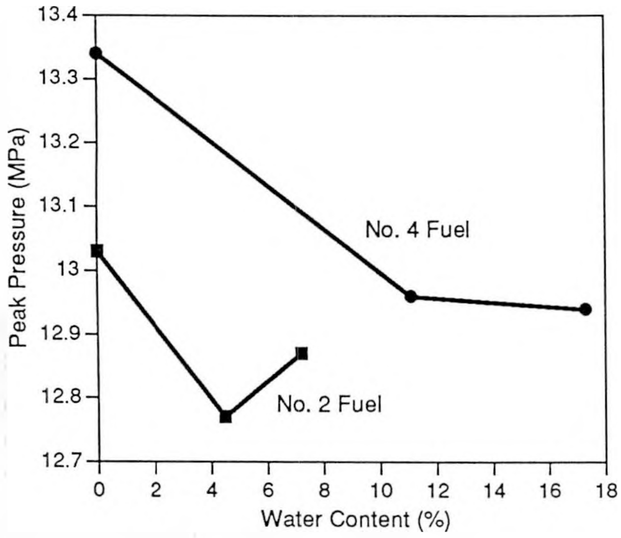

Fig. 5 Comparison of peak cylinder pressures with no. 2 and no. 4 diesel fuels (100% load, 37.3 kW, 35% O_2; baseline peak pressure= 11.3 MPa)

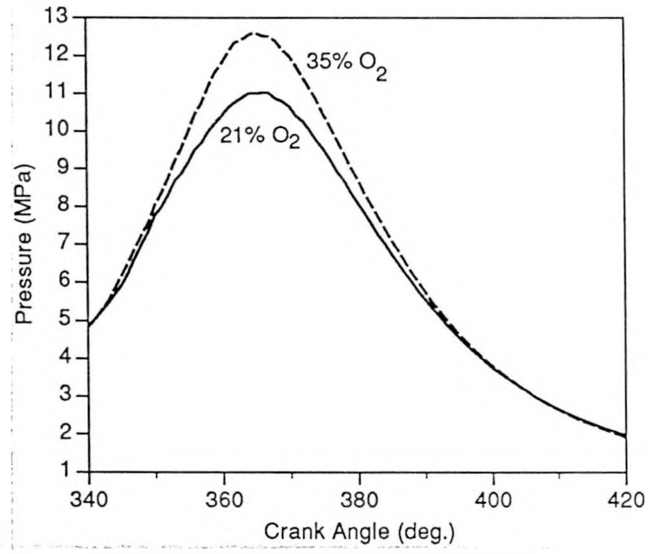

Fig. 6 Effect of intake oxygen levels on cylinder pressure (no 2. fuel, 100% load, 37.3 kW, no water)

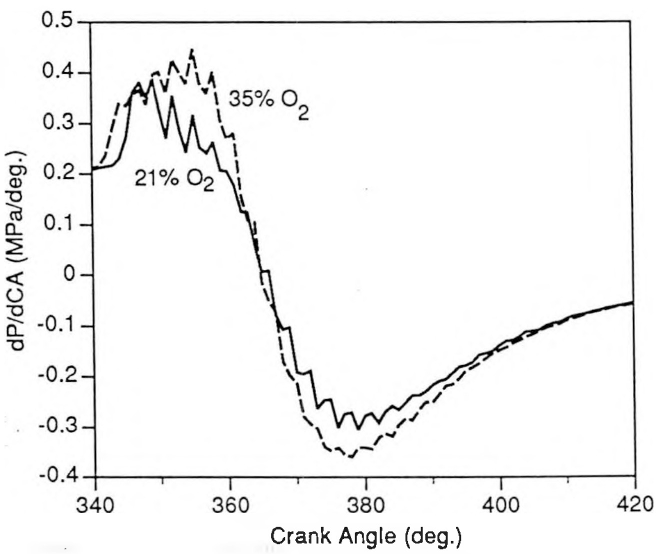

Fig. 7 Effect of intake oxygen levels on rates of cylinder pressure rise (no. 2 fuel, 100% load, 37.3 kW, no water)

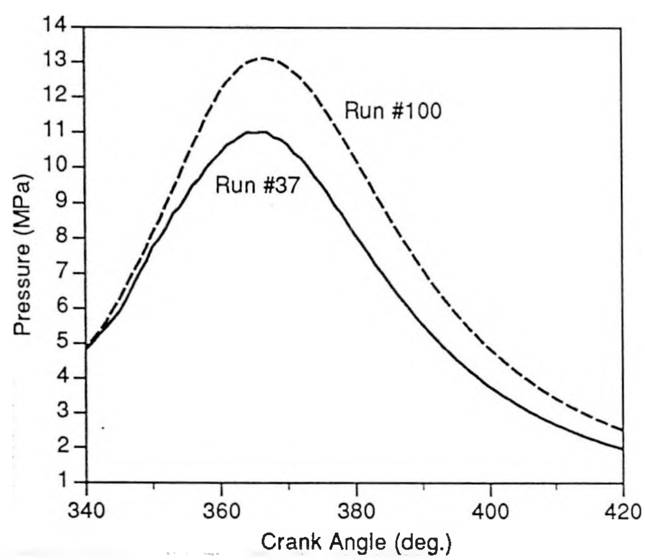

Fig. 8 Effects of water in the fuels, increased oxygen in the intake air, and increased power level on cylinder pressure (no. 2 fuel, 100% load; #37 0% water, 21% O_2, 37.3 kW; #100 6.9% water, 35% O_2, 56 kW)

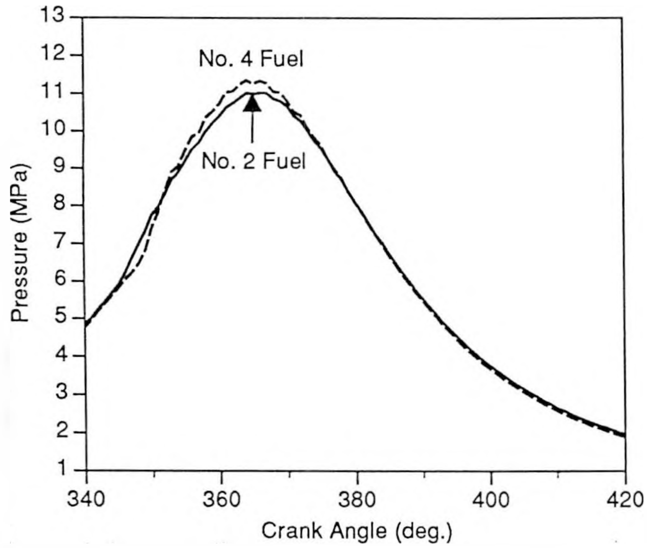

Fig. 9 Comparison of cylinder pressures with no. 2 and no. 4 diesel fuels (100% load, 37.3 kW, 21% O_2, no water)

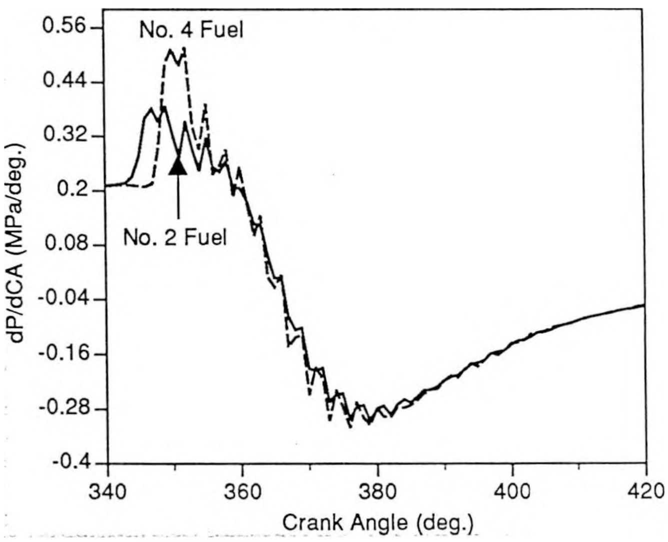

Fig. 10 Comparison rates of pressure rise with no. 2 and no. 4 diesel fuels (100% load, 37.3 kW, 21% O_2, no water)

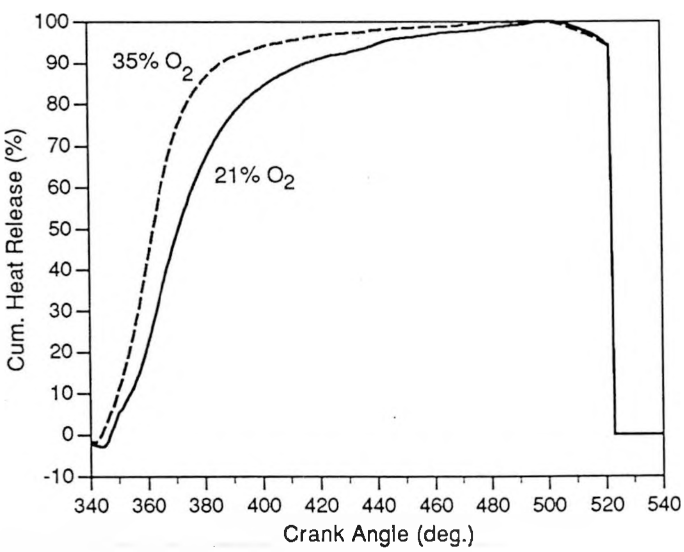

Fig. 11 Effect of oxygen on cumulative heat release rates (no. 2 fuel, 100% load, 37.3 kW, no water)

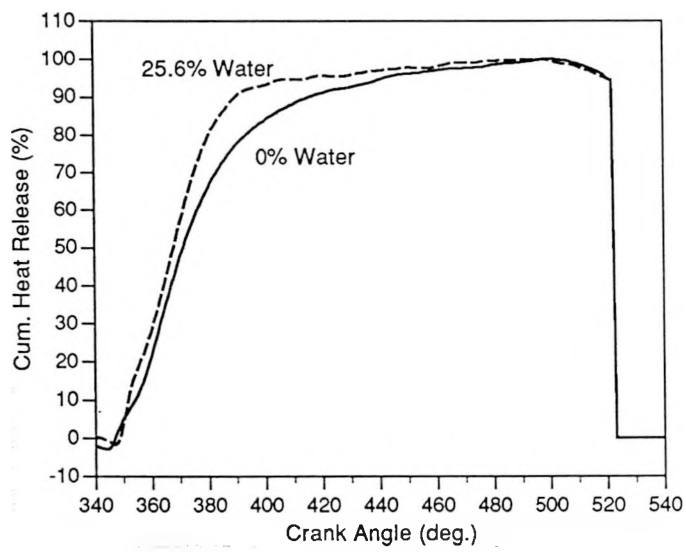

Fig. 12 Effect of oxygen on cumulative heat release rates (no. 2 fuel, 100% load, 37.3 kW, 21% O_2)

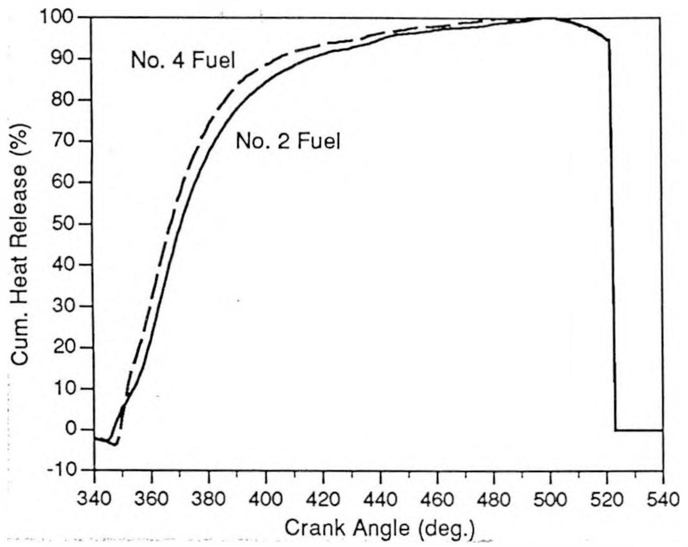

Fig. 13 Cumulative heat release with no. 2 and no. 4 diesel fuels (100% load, 37.3 kW, 21% O_2, no water)

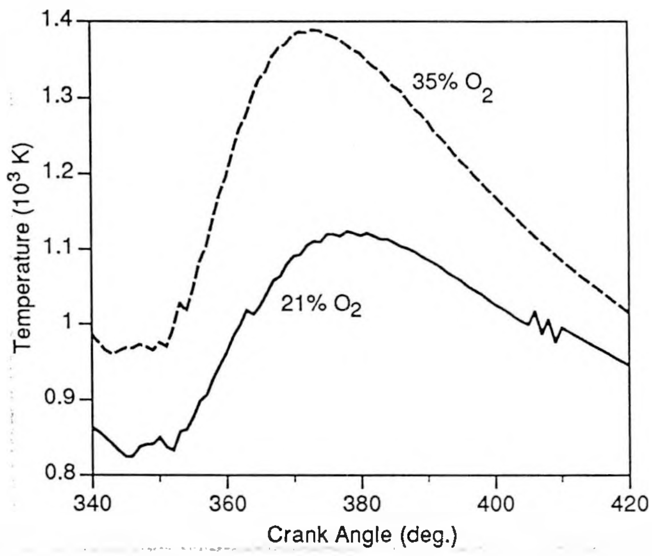

Fig. 14 Effects of oxygen level on calculated gas temperatures (no. 2 fuel, 100% load, 37.3 kW, no water)

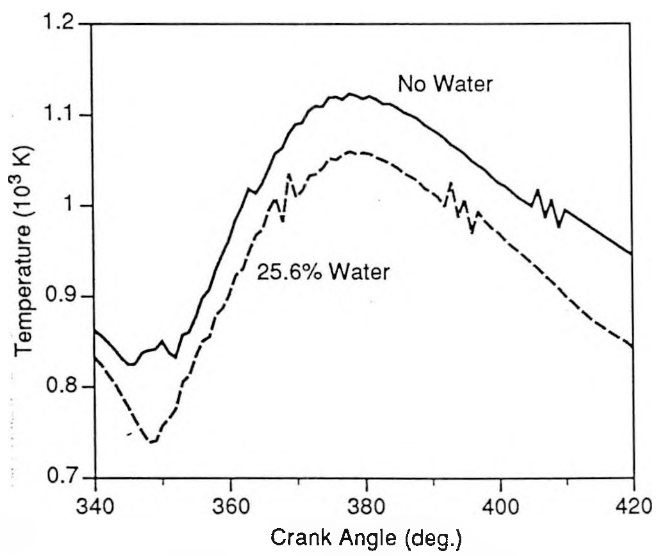

Fig. 15 Effects of water in the fuel on calculated gas temperatures (no. 2 fuel, 100% load, 37.3 kW, 21% O_2)