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EFFECTS OF OXYGEN ENRICHMENT AND FUEL EMULSIFICATION ON DIESEL ENGINE PERFORMANCE AND EMISSIONS

by
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ABSTRACT

Argonne National Laboratory (ANL), in cooperation with AutoResearch Laboratories, Inc. (ALI), has completed a series of tests on a single-cylinder, direct-injection diesel engine coupled to an oxygen-enriching membrane system. The data from the first series of tests using bottled oxygen have been previously reported. That series of tests included no examination of the effects of changing the injection timing, which is an important operating parameter that affects NO_x emissions and efficiency. In the second test series, the subject of this paper, the effects of injection timing were investigated. In addition, an oxygen-enriching membrane was used to supply combustion air. Use of bottled oxygen in any real diesel engine application would be a safety hazard, so bottled oxygen is unlikely to be used in commercial engine applications. For this reason, it is important to demonstrate an engine system with an on-line oxygen-enriching device.

Tests were conducted with #2 and #4 diesel fuels. The data indicated that NO_x emissions increase when the oxygen level is increased from 21 to 27%, but retarding the injection timing by 11 degrees crank angle significantly reduced the NO_x emissions. The effect on NO_x reduction of retarding the injection timing is greater at higher oxygen levels. The water emulsification of the fuels also reduced NO_x emissions significantly (Sekar et al., 1990a).

It was shown in both series of tests that oxygen-enriched combustion air reduced particulate emissions, smoke, and ignition delay. The effect on ignition delay resulted in a favorable NO_x vs. fuel consumption trade-off when the injection timing was changed. The collective data lead to the conclusion that an optimum set of the major operating variables, including (1) oxygen level in the combustion air, (2) water level in the fuel, and (3) injection timing, could lead to a diesel engine system that has (i) significantly lower particulates, smoke, and NO_x emissions, without loss of efficiency; (ii) the ability to use lower-cost heavy liquid fuels; and (iii) the potential for increasing the power output by as much as 50% with only a nominal increase (about 15%) in peak cylinder pressure.

INTRODUCTION

The concept of using oxygen-enriched air for diesel engine combustion has been studied by several researchers over the last two decades. The main motivation for oxygen enrichment is to lower the smoke and other exhaust emissions, as well as to improve the thermal efficiency. Wartinbee (1971) considered the concept of oxygen enrichment for spark-ignition engines but rejected it due to the difficulties involved in controlling NO_x emissions caused by oxygen enrichment. Quader (1978) studied the combustion mechanisms of oxygen enrichment; the concept was again rejected due to the NO_x and the fuel-consumption penalties that were encountered. Ghojel et al. (1983) and Iida et al. (1986) published their work on indirectly injected and directly injected diesel engines, respectively. Later, Iida and Sato (1988) found that the increased NO_x could be controlled by retarding the injection timing, which is made possible by the reduced ignition delay.

The application of the oxygen-enrichment concept to diesel engines is being reviewed in the context of particulate emissions standards proposed by the U.S. Environmental Protection Agency (EPA) that will go into effect in 1994. Since oxygen enrichment can potentially reduce smoke and particulate emissions significantly, this technology may provide a new option to solve diesel engine emissions problems. Recent work by engine developers (Watson et al., 1990; Willumeit and Bauer, 1988) indicates a renewed interest in the concept.

In parallel developments, funded primarily by the U.S. Department of Energy (DOE), significant advances were reported in practical oxygen-enrichment devices, such as "asymmetric hollow fiber" membranes that could be used for various end-use applications (Whipple and Ragland, 1989; Gollan and Kleper, 1985; Kobayashi, 1987). Argonne National Laboratory (ANL) undertook a systematic research project on the application of oxygen enrichment to stationary diesel engines. Although the concept offers several advantages in terms of performance and emissions, oxygen-enriched diesel engines cannot be commercialized in stationary or transportation applications

in the U.S. without a definite means of controlling the NO_x emissions. Hence, the use of water injection, in the form of emulsified fuel, was included as part of the ANL research. Water injection has been previously studied and reported to reduce NO_x (Valdmanis and Wulfhorst, 1970; Greeves et al., 1976). Analytical studies (Assanis et al., 1990; Cole et al., 1990) of the performance, emissions, and economic aspects of the diesel engine with oxygen enrichment and emulsified fuels have revealed that significant decreases in smoke, particulates, and other emissions (except NO_x), as well as decreased ignition delays, are possible. At the same time, excellent increases in power density and slight increases in efficiency could be achieved. In the next phase of the project, ANL conducted tests on a single-cylinder diesel engine to obtain performance, emissions, and cylinder-pressure data. Data from the first series of engine tests, in which bottled oxygen was used to increase the oxygen level of the combustion air, have been previously published by ANL (Sekar et al., 1990a; Sekar et al., 1990b; Sekar et al., 1990c). Although that test series was very useful for quantifying the benefits and the challenges to engine performance and emissions, two major items could not be included. The effects of fuel injection timing and use of an actual on-line oxygen-enriching membrane as part of the engine system should be investigated. This report documents these two aspects of the research.

OBJECTIVES

The main objective of the series of tests considered in this paper was to show that an oxygen-enriching membrane can operate as part of a diesel engine system. It was intended to repeat some data points from the first series of tests by Sekar et al. (1990a, b, and c) to confirm the benefits of and problems with oxygen-enrichment, fuel emulsification, and use of heavier base fuels. The second objective was to obtain performance, emissions, and cylinder-pressure data at three different fuel injection timings to determine the effect of fuel injection timing on engine performance and on the combustion process.

EXPERIMENTAL SET-UP

Engine and Fuels Used

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

The engine is designed to run on #2 diesel fuel. The objective of this project is to test the engine on a less refined fuel, such as #6 diesel. Because it was felt that the engine might not run smoothly on # 6 diesel fuel without extensive modifications, it was decided to compromise and test the engine on # 4 fuel, which is generally used in marine applications. Introduction of water into the combustion process was accomplished by emulsifying the two base fuels with distilled water and a small percentage of stabilizing chemical additive. Three levels of water content were tested with each base fuel.

The Oxygen Supply System

An oxygen-enriching membrane was available from a previous project (see Whipple and Ragland, 1989; Gollan and Kleper, 1985).

Table 1 Test Engine Specifications

Parameter	Value
Number of Cylinders	1
Bore (mm) × Stroke (mm)	137 × 165
Displacement (L)	2.44
Engine Speed (rpm)	1800
Injection Timing (°btdc)[1]	33
Compression Ratio	14.5
Peak Cylinder Pressure (bar)	110

A schematic diagram of the air supply system is shown in Fig. 1. An air compressor was used with a cooler and dehumidifier to supply feed air to the membrane. The nitrogen-rich air was discarded, and the oxygen-rich air and the shop air were mixed in a large tank before the intake manifold of the engine. A micro-fuel-cell type (Teledyne model 326A) oxygen sensor located in the engine intake manifold was used to measure the intake oxygen content of the air entering the engine. Elaborate safety systems were provided to handle oxygen. The engine crank case was purged with nitrogen for added safety while running the engine. All the other test set-up and measurement details were exactly the same as in the first series of tests (Sekar et al., 1990a, b, and c).

Test Matrix

Two engine operating conditions were tested in this series. "50% Load" is defined as the engine operating conditions (intake manifold pressure, exhaust manifold pressure, and mass flow rate of air plus oxygen) corresponding to 50% brake power level of the base engine, which is 18.65 kW (25 hp). "100% 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 the "50% load" point and 140 cm Hg abs. at the "100% load" point. The exhaust manifold pressure was maintained at 81 cm Hg abs. throughout. Only constant power output data were obtained this time, since the cases of constant exhaust-to-intake-oxygen ratio and constant exhaust-oxygen level already have been reported (Sekar et al., 1990a, b, and c). Only one intake-oxygen level, besides the base of 21%, was used. The membrane has the selectivity to produce up to 35% oxygen, but the permeability was not adequate to provide the mass flow rate required by the engine to produce constant power. Hence, shop air was mixed with oxygen-enriched air from the membrane unit. The power had to be constant, so the intake-oxygen level of this system was adjusted to establish the equilibrium condition; in most test runs, this was at 25-27% oxygen in the intake air. Fuel emulsions were used with water contents of 0 and 5% by weight. Seventy-two test runs were made, and many graphs were plotted. Only a portion of the curves, showing most significant trends, are presented in this report. Overall, the test series was completed without any major engine problems.

[1]btdc = before top dead center. A timing of N degrees crank angle before top dead center is commonly indicated by N° btdc.

The base injection timing was 33° btdc. Two retarded timings of 27° and 22° btdc were used in this test matrix to investigate the effects of varying injection timing on engine performance and emissions.

DISCUSSION OF THE DATA

Membrane Performance

Initially the membrane alone was tested, with the engine shut off, to map the flow rate (permeability) and oxygen purity (selectivity) that could be achieved with the available membrane. (This membrane was not optimized for use with a diesel engine or for oxygen-enriched air as the product. The membrane was originally purchased by DOE for a membrane-development project in which the product was pure nitrogen and the oxygen-enriched air was just a waste stream.) Figure 2 illustrates the membrane performance. The membrane is capable of producing up to 35% oxygen, but the flow rate of oxygen-enriched air is low (only about 30% of the inlet air flow rate). This figure shows two major problems connected with the application of membrane technology to engines. First, the high pressure levels used in the experiment are generally not available in an engine application. Second, the "yield" of oxygen-enriched air, compared to the membrane inlet air flow rate, needs to be improved. Such an improvement would reduce both the parasitic losses and the cost.

Engine Performance

The major independent variable of interest in this part of the investigation was injection timing; all the data are presented as a function of injection timing. As shown in Fig. 3, the thermal efficiency decreases as the injection timing is retarded from 33° to 22° btdc. This decrease is a well-known characteristic of diesel engines. However, the same data at a higher oxygen level seem to indicate a different optimal timing, at approximately 27°. The thermal efficiency is slightly, but consistently, higher at higher oxygen levels. Figure 4 illustrates a similar trend when the fuel was emulsified with 5% water. The gains in power density potential are expected to be the same as those reported earlier (Sekar et al., 1990a, b, and c). It is important to increase the engine power rating when oxygen-enriched air is used. Part of the increased power is needed to offset the parasitic losses of the membrane. At the 50%-load point and with a #4 base fuel, similar trends in performance were noted.

Emissions

One of the conventional means of controlling NO_x emissions is to retard the injection timing. However, when the timing is retarded the brake specific fuel consumption (bsfc) increases. Hence, the actual engine timing is determined as a trade-off between NO_x and bsfc. The effect of injection timing on NO_x emisions is presented in Fig. 5. The reduction in NO_x observed in the base case (21% oxygen), as well as in the higher-oxygen-level case (25% oxygen), followed predictable trends. At 25% oxygen the effect of injection timing on NO_x emissions was slightly more pronounced than in the base case. Figure 6 is a typical NO_x vs. bsfc trade-off curve. At higher oxygen levels, retarding the injection timing has a large impact on NO_x but very little impact on bsfc. This could be explained by the reduction in ignition delay when oxygen-enriched air is used for combustion. This is a characteristic that could be used to advantage when the engine is optimized for oxygen-enriched combustion air. Similarly, NO_x emissions and particulate emissions are also controlled in a trade-off mode. When injection timing is retarded to decrease NO_x emissions, particulate emissions increase. However, as shown in Fig. 7, when oxygen-enriched air is used, the effect on particulate emissions of retarding the timing is insignificant compared to the effect with standard air. The results regarding the use of neat #4 diesel fuel and fuel-water emulsions confirmed the earlier trends.

Combustion

Combustion in diesel engines is usually analyzed by measuring the cylinder pressure as a function of crank angle. Figure 8 shows the effect of injection timing on cylinder pressures during the combustion portion of the cycle. Figure 9 presents the corresponding data at a higher oxygen level. Comparison of these two figures suggests that an oxygen-enriched diesel engine is likely to behave exactly the same as a conventional diesel engine. Corresponding heat release diagrams are presented in Figs. 10 and 11. Again, these figures indicate very close similarities between a conventional and an oxygen-enriched diesel engine. In terms of technology transfer, this is encouraging, because it implies that engine modifications will be minor; thus, engine manufacturers are more likely to consider these technologies for incorporation into their products. The effects of oxygen enrichment on peak cylinder pressure and the smoke-limited gross engine power output are shown in Fig. 12. These data were obtained in the first series of tests using bottled oxygen. Given a nominal increase in cylinder pressure, one obtains a dramatic increase in power density potential. This indicates that engine manufacturers might be able to incorporate oxygen-enrichment technology without major engine changes.

CONCLUSIONS

1. Oxygen enrichment of combustion air is a viable technology for diesel engines. The demonstration of a membrane separator to enrich the oxygen as part of a diesel engine system proves that the concept is technically feasible. No major engine modification is needed to incorporate the membrane system.

2. The remarkable increase in power density potential demonstrated in these tests is important in industrial cogeneration and power generation plants. The oxygen enrichment system has considerable parasitic losses, and part of the increased power from the engine will be utilized to overcome these losses. The net power gain should help to reduce the capital cost of the plant and to offset the capital cost of the membrane system.

3. Oxygen enrichment slightly improves thermal efficiency, and hence fuel consumption.

4. Oxygen enrichment, by itself, increases NO_x emissions if the power output of the engine remains unchanged. Retarding the injection timing and introducing water into the combustion process can significantly reduce the NO_x emissions.

5. Particulate emissions data are mixed. The base engine has a low level of mass particulate emissions. The measurement accuracy of changes in particulate emissions due to oxygen enrichment was not adequate to give consistent data. The general trend is for the particulate matter to decrease with increasing oxygen levels in the air.

6. Oxygen enrichment and the resulting higher power output increases the cylinder pressures. The peak pressure is increased by about 15% when the power is increased by 140%.

7. Both oxygen enrichment and water emulsification of fuel show a definite trend in the heat release diagrams. The higher proportion of the energy release occurs in the early part of the combustion process. This trend should be taken into consideration when the combustion process geometry and parameters are optimized.

8. No attempt was made in these experiments to optimize the operating variables. By employing these two technologies, i.e., oxygen enrichment and fuel emulsification, an engine designer will have two more degrees of freedom to improve the overall system performance and emissions.

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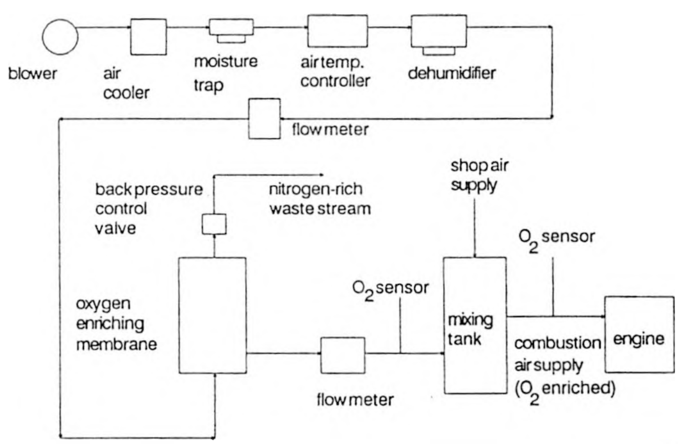

FIG. 1 Schematic Diagram of Oxygen Supply System for Engine Tests

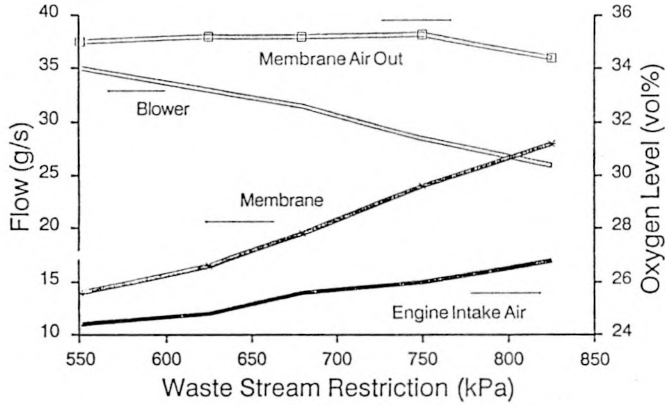

FIG. 2 Performance Map for the Air Separation Membrane

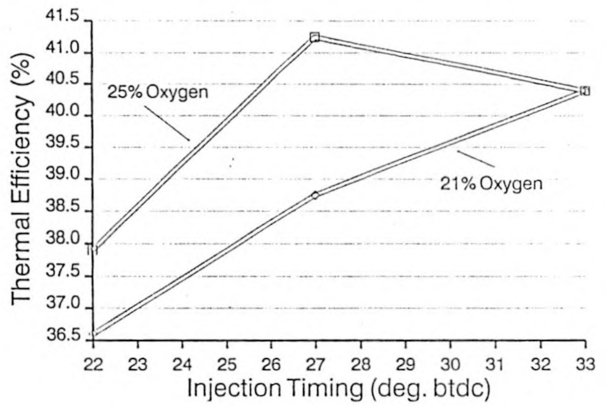

FIG. 3 Effect of Injection Timing on Thermal Efficiency -- Oxygen-Enriched Air and Standard Fuel, 50 bhp, No Water

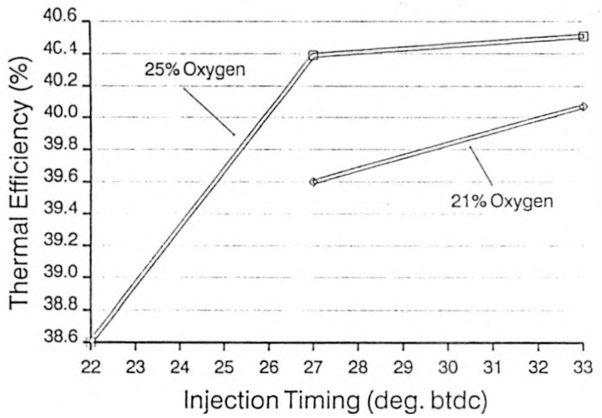

FIG. 4 Effect of Injection Timing on Thermal Efficiency -- Oxygen-Enriched Air and No. 2 Diesel Fuel Emulsified with 5% Water, 50 bhp

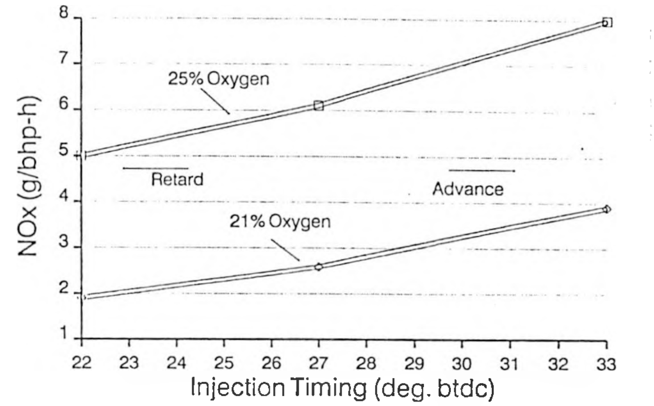

FIG. 5 Effect of Injection Timing on NO_x, 50 bhp, No. 2 Diesel Fuel, No Water

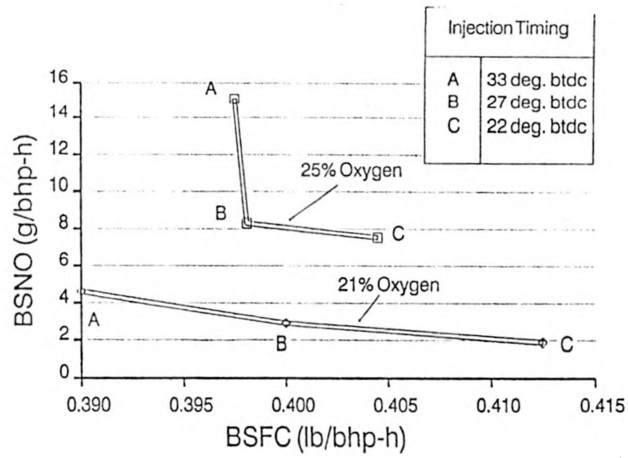

FIG. 6 Trade-Off between Brake Specific Fuel Consumption (bsfc) and NO_x ($BSNO_x$) -- No. 2 Diesel Fuel, 25 bhp, No Water

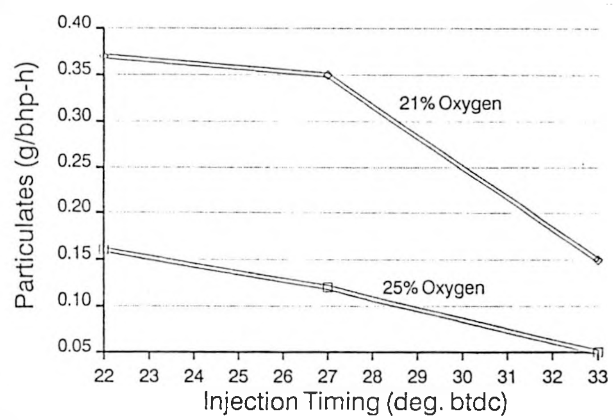

FIG. 7 Effect of Injection Timing on Particulate Emissions -- Oxygen-Enriched Air and No. 2 Diesel Fuel, 50 bhp, No Water

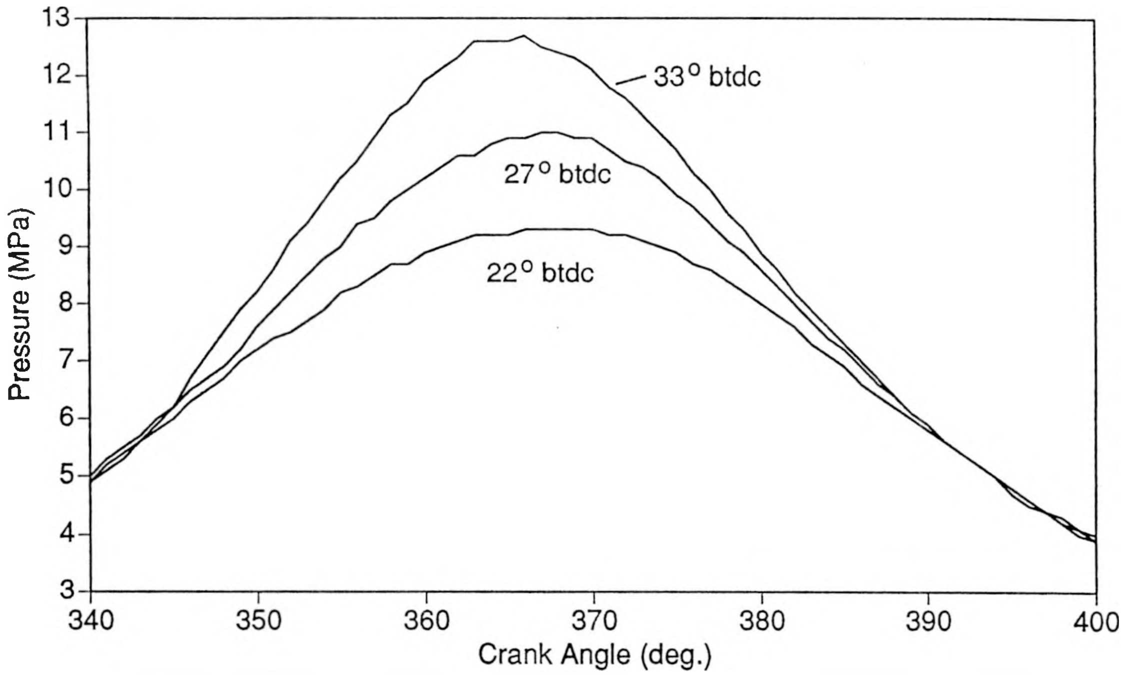

FIG. 8 Effect of Injection Timing on Cylinder Pressure, Baseline Diesel Engine -- 21% Oxygen, No. 2 Diesel Fuel, Full Load, No Water

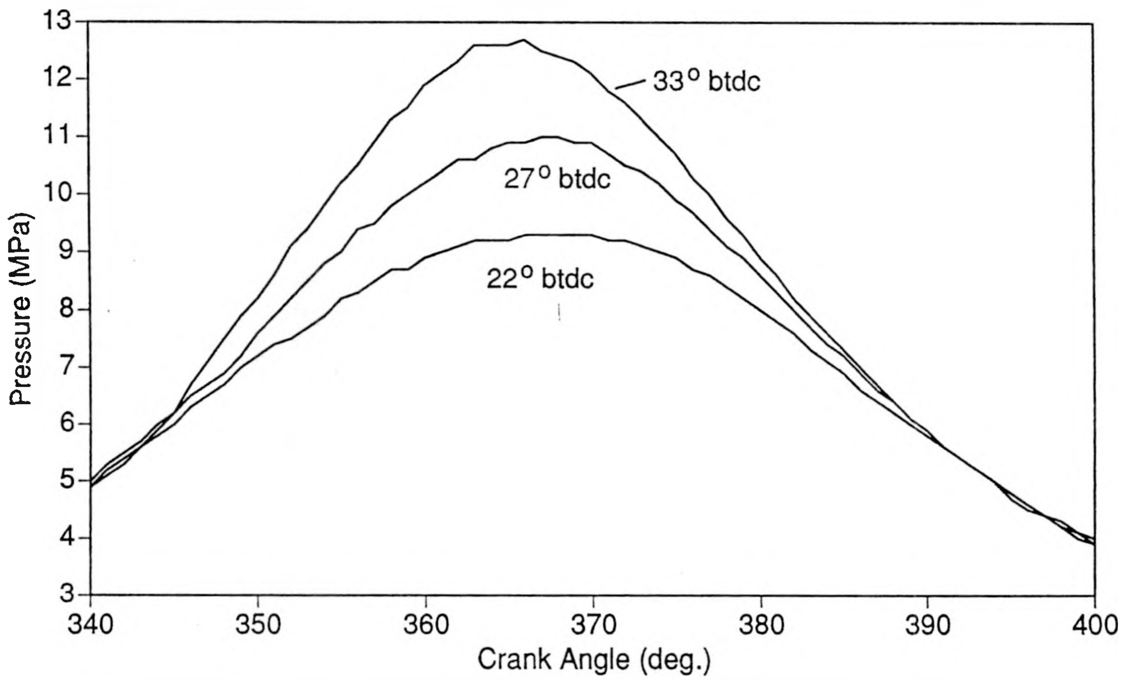

FIG. 9 Effect of Injection Timing on Cylinder Pressure, Oxygen-Enriched Diesel Engine -- 25% Oxygen, No. 2 Diesel Fuel, Full Load, No Water

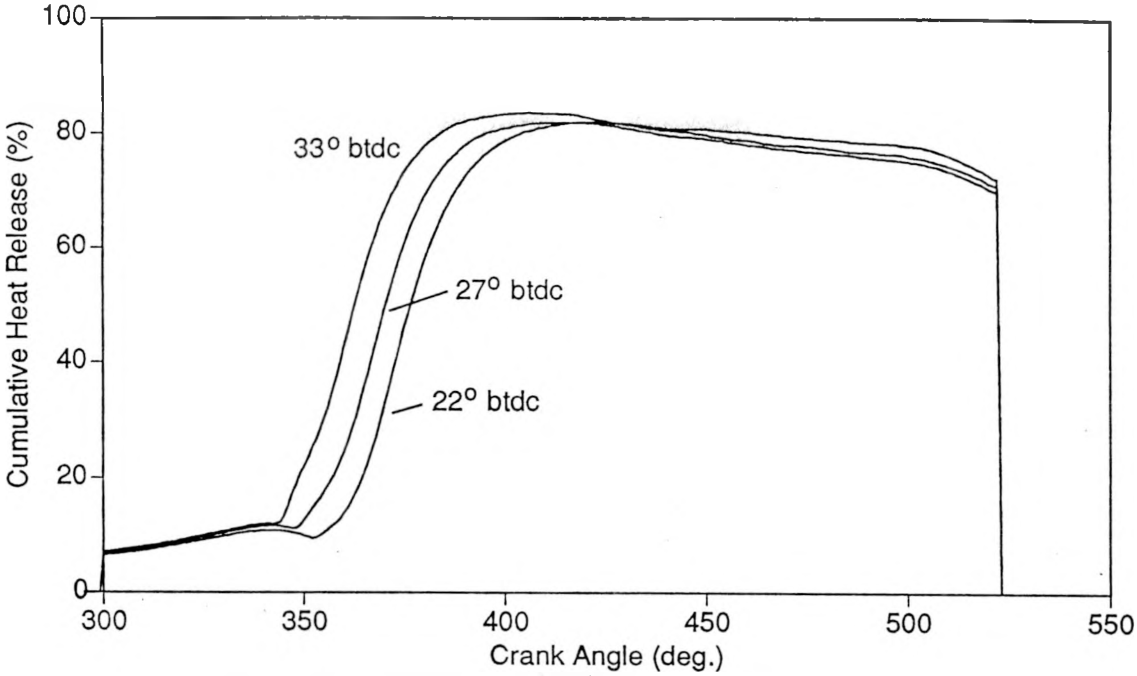

FIG. 10 Effect of Injection Timing on Cumulative Heat Release Rate, Baseline Diesel Engine -- 21% Oxygen, No. 2 Diesel Fuel, Full Load, No Water

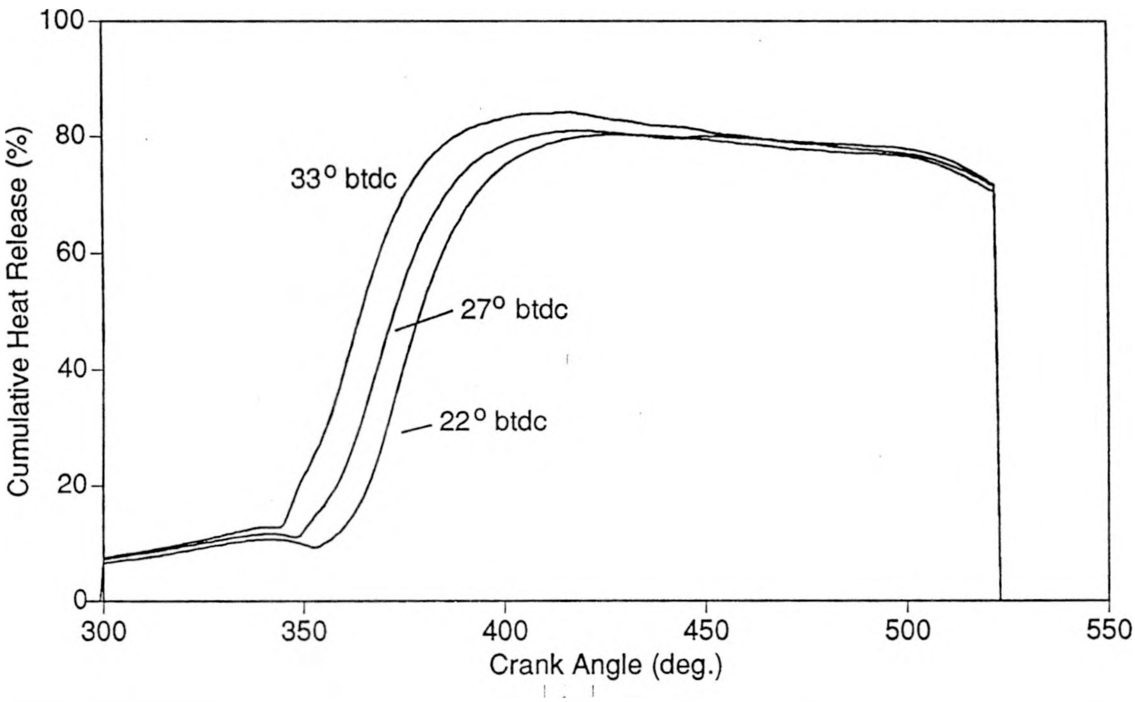

FIG. 11 Effect of Injection Timing on Cumulative Heat Release Rate, Oxygen-Enriched Diesel Engine -- 25% Oxygen, No. 2 Diesel Fuel, Full Load, No Water

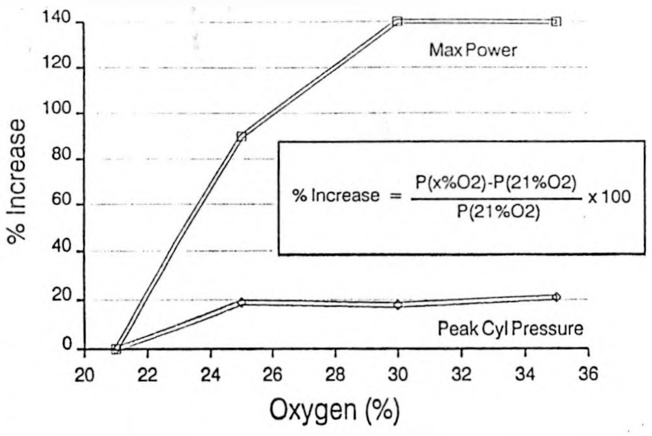

FIG. 12 Effect of Oxygen Level on Maximum Power Output and Peak Cylinder Pressure

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