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COMBUSTION OPTIMIZATION STUDIES
FOR STRATIFIED CHARGE AND
DIESEL ENGINES

Progress Report
for Period October 1, 1978 - September 30, 1979

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ABSTRACT

The objectives of the program are (1) To assess the feasibility and operating characteristics of the following high compression, spark ignition (or self-ignition), stratified charge (or diesel) engine configuration: compression ratio: 16; open chamber; direct fuel injection; unthrottled operation; 615 cc/cylinder; explored speed range 1000-4000 rpm (expected practical range 600-6000 rpm); fuels: ethanol-diesel mixtures; spark ignition (stratified charge) or self-ignition (diesel). (2) To continue the development and the testing of physical and numerical aspects of multi-dimensional combustion models in order to assess and improve their accuracy and to reduce their computation time. (3) To contribute to the achievement of a more fundamental and detailed understanding, characterization, and command of the processes which control efficiency and emissions in internal combustion engines.

The objectives are to be met by comparing, locally and instantaneously, calculated and measured density gradients in the flow field due to direct fuel injection. The computed two-dimensional, unsteady results will be compared with Schlieren film data from a transparent-piston, transparent-head, valveless, engine.

Progress to date is reasonably within the contract schedule in that: (1) the transparent-piston, transparent-head engine is in routine use for visualization experiments; (2) the gaseous fuel injector is routinely used with gaseous propane as a fuel injected into the motored engine; (3) high speed filming and short duration pulsed light single exposure techniques are being used to obtain shadow and schlieren records of gaseous and liquid jets; (4) an LDV system for measuring in-cylinder velocities has been implemented and data is presently being taken and analyzed; (5) engine cylinder pressure data can now be taken and reduced with the minicomputer; and an infrared emission absorption technique has been used to measure engine cylinder temperature; (6) an alternative approach to the modeling of gaseous jets has yielded a characteristic time for steadying of the jet, which in the long run should allow a more efficient computational procedure; (7) work on the definition of appropriate equations for thick sprays has continued; (8) two DISC meetings have been attended, one of which was hosted by Princeton, and the results of the program have been made known to researchers and automotive industries; and (9) the pulsed illumination television system has been successfully used to obtain visual data on engine cyclic variations.

Future work is expected to continue according to the initially proposed work schedule.

OBJECTIVES AND APPROACH

The objectives of the program are (1) To assess the feasibility and operating characteristics of the following high compression, spark ignition (or self-ignition), stratified charge (or diesel) engine configuration: compression ratio: 16; open chamber; direct fuel injection; unthrottled operation; 615 cc/cylinder; explored speed range 1000-4000 rpm (expected practical range 600-6000 rpm); fuels: ethanol-diesel mixtures; spark ignition (stratified charge) or self-ignition (diesel). (2) To continue the development and the testing of physical and numerical aspects of multi-dimensional combustion models in order to assess and improve their accuracy and to reduce their computation time. (3) To contribute to the achievement of a more fundamental and detailed understanding, characterization, and command of the processes which control efficiency and emissions in internal combustion engines.

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Significant New Results

- (1) The determination of the characteristic time and space scales for the steadying of transient, gaseous, laminar jets.
- (2) The demonstration of the suitability of the pulsed illumination television system for the studying of engine cyclic variations.

PROGRESS TO DATE

Progress is reasonably in line with the contract schedule given in the proposal of July 11, 1977 and on Page 7. The Closed Circuit Television System, added as a separate task in the last Progress Report has been shown useful in studying cyclic variations. A brief task-by-task report follows. Some of the details are given in the three papers of the appendices but much of the recent progress is yet to be written up for formal publications.

Task 1: Modification of the Single Cylinder Engine

The conversion of this engine to a transparent-piston, transparent-head configuration is complete and it is routinely used for experiments. The engine has been motored and fired with gaseous fuel at compression ratios of 8.5 and 16, to speeds of 1000 rpm. The first transparent piston used in the engine did eventually crack along the inside of a piston ring groove, but only after many hours under firing conditions. For visualization studies, the migration of crankcase oil to the windows is a problem, but has been controlled (through closing of the oil passageway in the connecting rod, the use of guard flaps at the bottom of the cylinder, and periodic cleaning and inspection of the cylinder and piston) to the point where the engine can be run for some time ($\sim$ hours intermittently) without oil spotting.

Task 2: Implementation of Gaseous Fuel Injection

The gaseous fuel injector has now been operated with gaseous propane as a fuel, at pressures to 1000 psig, injecting into lab air and into the motored engine at compression ratios 8.5 and 16. The fuel is vaporized by passing it through a heating unit at about 400°F and then to the injector which, depending on the propane flowrate is also heated to temperatures between 250°F and 400°F.

Task 3A: Schlieren and/or Shadowgraph Recording of Gas and Liquid Jets Without Combustion

At the last DISC meeting several sections from high-speed films (3000 pps) were shown which displayed shadowgraph records of liquid propane jets (fuel pressure = 1000 psig) sprayed into lab air and into the motored engine (CR = 16, engine speed = 500 rpm) with swirl and gaseous propane jets into lab air (fuel pressure = 600 & 1000 psig; fuel temperature = 125° & 180°C) using the special gaseous fuel injector with a single orifice nozzle (0.012" dia) in all cases. Since that time, shadowgraph high-speed films have also been taken of gaseous propane injected into the motored engine. However, tuning of the system to obtain clear, sharply defined images of the gaseous fuel jets has remained an elusive problem. Steps taken to improve the quality of the films include: increasing the nozzle orifice diameter (to increase the total mass flow and momentum of the jet); reducing the fuel pressure (to reduce the relative velocity between fuel

and air and thus try to diminish the mixing of fuel and air); decreasing the compression ratio to diminish the effects of fuel impingement on the head and piston windows; using high contrast developers in the film processing; and improving the engine scavenging to enhance the contrast. Also, the activating liquid fuel in the fuel injector has apparently been leaking past the seals and been injected with the gaseous propane and finally condensing on the windows making visualization more difficult. To remedy this, the injector has been modified by the addition of a small drilled hole through the injector body to the spindle surface at a point between two sets of seals, thus allowing any actuating fuel getting by the seals to leak off to atmosphere before reaching the propane.

Presently, a single pulse (at a particular crankangle) technique employing Polaroid film to obtain more rapid results is being used and effort continues at increasing the sensitivity of the optical system to obtain visual records of adequate contrast and quality of gaseous and liquid sprays to enable meaningful comparisons.

Task 3B: Schlieren and/or Shadowgraph Recording of Gas and Liquid Jets with Spark Ignition

The transparent piston, transparent-head engine will be run in a firing mode with direct fuel injection in the near future. This task was delayed while the visualization of fuel jets was improved, but it is now felt that firing may alleviate problems due to condensed fuel on the windows.

Task 3C: Not yet active.

Task 4: Gas Velocity Measurements

A second transparent-piston, transparent-head (TPTH) engine has been built and installed on a newly acquired Waukesha CFR-48, high-speed (4000 RPM) crankcase. This engine is identical to the first TPTH engine used in the photographic studies of gas and liquid jets except for the added high-speed capability. This second TPTH engine was built specifically for the application of laser techniques. The first technique which is being employed in this engine is laser Doppler velocimetry (LDV) for the measurement of gas velocity as a function of position in the combustion chamber and crankangle.

A one-component LDV system has been purchased, received, and put into operation. The first measurements in the TPTH engine under motored conditions are currently being taken. The LDV system being used for this work is a dual-beam system. A Bragg cell is used to eliminate the directional ambiguity of the measured velocities. The collection optics can be set up in either the backward scatter or forward scatter mode. A unique advantage of the TPTH design is the ability to operate in the forward scatter mode which enhances the LDV signal level by two to three orders of magnitude. The optics were all purchased from TSI, Inc.

The current measurements are being made using the naturally occurring water vapor and oil vapor droplets rather than separately introduced seed particles. The accuracy of the velocity measurement when using these droplets is under evaluation.

The 5145 Å output of a Lexel argon ion laser (4 watts multimode) is being used for this work. This laser was selected for its TEM₀₀, single frequency output.

A TSI Model 1990 counter processor is used to process the LDV signals. The digital velocity output of the counter processor and the simultaneous digital crankangle signal are recorded on a Hewlett-Packard 21MX disc based minicomputer system. A 16 channel, high-speed (250 kHz) digital multiplexer has been designed and built specifically for interfacing the TSI counter processor to the Hewlett-Packard minicomputer.

The funds for the LDV optics and electronics, the argon ion laser, the minicomputer and the interface have been provided by our department and industrial donations. This program supports only part of the personnel costs associated with the LDV task. Support for it is also being provided by Volkswagen AG of West Germany and the National Science Foundation.

Task 5: Measurement of Engine Operating Parameters

In order to characterize the cylinder charge precisely, simultaneous measurements of engine cylinder pressure, temperature, and composition must be made, as stated in the previous progress report. Engine cylinder pressure (by piezoelectric transducer) is now routinely measured and is, when desired, recorded and analyzed by the Hewlett Packard minicomputer to yield pressure as a function of crankangle as well as indicated work.

An apparatus for employing an infrared emission-absorption technique to obtain engine cylinder temperature data has been designed, built, and tested on the transparent-piston, transparent-head engine. The system responds to the emission and absorption characteristics of CO₂ and water vapor in the cylinder charge. To the present date, the system has been successfully used to measure temperature as a function of crankangle on the compression stroke of the cycles immediately following combustion. From simultaneous measurement of pressure and temperature, the mass of the trapped charge has been computed.

As it becomes more urgent to precisely know the size and equivalence ratio of the trapped charge for combustion computation-experiment comparisons, more effort will be expended in improving the temperature measurements and in making composition measurements.

Task 6A: Modeling of Gaseous Jets Without Combustion

Although two-dimensional unsteady computations of gaseous jets could be made with the same codes, available at Princeton and elsewhere, with which the more comprehensive two-dimensional unsteady combustion flowfields are being computed, we have taken a different approach that in the long run should be considerably more efficient.

The difficulty with computing gaseous jets in engines is due to the vastly different scales of the jet nozzle, which is of the order of 100μ , and of that of the flowfield, which is of the order of 10 cm. Thus, computations with uniform mesh sizes are either inaccurate or unacceptably long and nonuniform and time varying meshes present their own difficulties. However, if one can predict how long it takes for steady state to be reached at, say, 10 nozzle diameters, then one can start the jet computations after that time with a larger mesh size and without losing accuracy. Accordingly, two-dimensional, unsteady computations are being made and the parameter of interest is the time necessary for steady state to be reached at any given downstream location. Strictly, the steady configuration of a jet in an infinite medium is reached exponentially after an infinitely long time. But at any given location, 99% of steady state values, or any other similar percents, are reached within finite times which can be expressed in terms of a characteristic steadying time.

Our numerical solutions of the conservation equations indicate that, for a laminar jet in an incompressible medium, the characteristic steadying time is D^2/ν where D = diameter, ν = kinematic viscosity, $Re = uD/\nu$ = Reynolds number. The only other previous attempt at identifying the characteristic steadying time appears to be that of Abramovich and Solan, who deduced it by curvefitting their own experimental data and concluded it to be $D^2/\nu Re^{1/2}$ at the characteristic distance $DR_c^{1/2}$. These time and length scales are different from those we have determined through the solution of the conservation equations. But the scatter in the Abramovich and Solan experimental data is such that both their scales and our scales satisfy them. Although we are confident that our scales are the correct ones, since they come from solutions of the complete conservation equation and not through curve fit of experimental data with large scatter, adequate experimental data for the resolution of the issue is presently not available.

The above approach to studying jets is more fundamental, more time consuming, and more promising than the one originally envisioned. Accordingly, Tasks 6B and 6C are likely to be pushed back in time to some extent.

Task 6B: Modeling of Gaseous Jets with Spark Ignition

This task is to be initiated in the near future.

Task 6C: Modeling of Gaseous Jets with Self-Ignition

This task is not yet scheduled for initiation.

Task 7: Comparison with Bomb Data

This task was completed earlier as described in the previous progress report. Additional findings from it are discussed in Appendix B.

Task 8: Modeling of Thick Sprays

Work on the definition of appropriate equations for thick sprays is proceeding in cooperation with the Los Alamos Scientific Laboratory. Mr. P. J. O'Rourke started his work as part of his Ph.D. program at Princeton on leave from LASL. Now, he is continuing it at Los Alamos, as part of his Ph.D. thesis and is being advised by Professor F. V. Bracco and Dr. F. H. Harlow. The task is a difficult one because little data is available of direct pertinence. Information on momentum, energy, and mass exchanges between gas and closely spaced drops is being extrapolated from corresponding data in the packed and fluidized bed literature as well as from the fields of meteorology and heat exchangers.

Task 9: Participation in DISC Meeting

We participated in and contributed two presentations to the 8th DISC meeting at Los Alamos Scientific Laboratory on September 7-8, 1978. We also hosted and contributed three presentations to the 9th DISC meeting on March 28-29, 1979 and look forward to the next meeting at General Motors.

Task 10: Development of a Pulsed Illumination Television System

The usefulness of this television system in obtaining visual data on the cyclic variation of flame propagation under premixed methane-air operating conditions with the transparent-piston, transparent-head engine has been demonstrated and the results were presented at the 1979 SAE Congress. For details please consult the paper of Appendix C. Current efforts are concentrated on improving the quality of the image by reducing drastically the laser light that gets to the camera between laser pulses.

TASKS

2. Implementation of Gaseous Fuel Injection

3B. Schlieren and/or Shadowgraph Recording of Gas and Liquid Jets with Spark Ignition

5. Measurements of Engine Operating Parameters

6A. Modeling of Gaseous Jets without Combustion

6B. Modeling of Gaseous Jets with Spark Ignition

6C. Modeling of Gaseous Jets with Self Ignition

7. Comparisons with Bomb Data

8. Modeling of Thick Sprays

9. Participation in DISC Meetings

10. Development of Pulsed Illumination Television System

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