N O T I C E

THIS DOCUMENT HAS BEEN REPRODUCED FROM MICROFICHE. ALTHOUGH IT IS RECOGNIZED THAT CERTAIN PORTIONS ARE ILLEGIBLE, IT IS BEING RELEASED IN THE INTEREST OF MAKING AVAILABLE AS MUCH INFORMATION AS POSSIBLE

Final Report

January, 1979 to January, 1980

on

NASA Grant NSG-3245*

COMBUSTION AND OPERATING CHARACTERISTICS

OF SPARK-IGNITION ENGINES

John B. Heywood, James C. Keck, Gian Paolo Beretta and Paula A. Watts

Sloan Automotive Laboratory

Department of Mechanical Engineering

Massachusetts Institute of Technology

Cambridge, Massachusetts   02139

March 28, 1980

1. BACKGROUND

At the present time, only a rough understanding of the flame propagation process in a spark-ignition engine exists. To predict engine operating characteristics and to design engine combustion chambers with high efficiency and low emissions, researchers have developed various approximate techniques to describe how a turbulent flame propagates across the combustion chamber. These techniques show promise for evaluating new design concepts and as research tools for understanding more about engine experiments. As yet, these approximate techniques are not sufficiently predictive. Generally, these models require empirical information about turbulence, flame geometry, heat release rate, diffusion, burning velocity and mixture motion. However, there are several problem areas where the coupling between the combustion process and the engine variables of interest is relatively weak. Under these conditions, engine models or simulations can be used to examine other aspects of engine operation.

In this grant program, two specific topics in this area were examined. The first of these, an engine combustion modeling activity, was directed at improving our understanding of the spark-ignition engine flame propagation process through an examination of an experimental data base collected previously on a transparent piston research engine in our Sloan Automotive Laboratory at M.I.T. The second activity used an existing spark-ignition engine cycle simulation and combustion model to examine the impact of turbocharging and heat transfer variations on engine power, efficiency and NO_x emissions.

This final report on the grant program summarizes the research findings. Section 2 describes the work on spark-ignition engine turbulent flame propagation and structure. Section 3 describes the results of the spark-

ignition engine cycle simulation studies on turbocharging and changes in heat transfer. The Appendix lists the theses and publications prepared on this work, with abstracts, where complete details of the research can be found.

2. DETERMINATION OF TURBULENT FLAME SPEED AND THICKNESS

The objective of this activity was to determine the rate of flame propagation and deduce information on the flame thickness and structure in a spark-ignition engine using an existing experimental data base which consisted of simultaneous records of cylinder pressure and flame front location from combustion movies.

During a one year stay at M.I.T. in 1977-78, Dr. M. Rashidi set up an experiment on a transparent-piston engine. The cylinder head on this engine set-up was a section of a Ford 400 CID V-8 engine cylinder head. The bore was 10.2 cm and the stroke was 8.89 cm. Optical access to the combustion chamber was obtained through the quartz piston, and high speed photography of the propagating flame was obtained by using a Hycam rotating-prism camera capable of taking up to 4000 pictures per second. A conventional pressure measurement was obtained from a piezo-electric pressure transducer and recorded by an on-line PDP 11 digital computer for further analysis.

One key advantage of having taken photographs through the piston, instead of through a transparent head, was that the valve configuration was not changed and the flow geometry was kept the same as in the original engine. Thus this data represent current practice engine designs.

Work on this grant has focused on the analysis of the synchronized pressure histories and photographic sequences that the experiment generated for each engine operating condition. The intent was to generate, with a

minimum of physical assumptions, information on the flame propagation rate
and the flame structure. Analysis of the pressure data using thermodynamic
based models permitted an estimate to be made of the rate of mass burning
throughout the combustion process. An analysis of the flame photographic data
provided information on flame front location, the inflamed volume, the shape
and area of the flame front and average flame front speed, all as a function
of time. From the combined analysis of cylinder pressure history and flame
photography, the speed with which unburned mixture enters or is entrained into
the flame front (the entrainment speed) was determined. A comparison of the
inflamed (i.e., within the flame) mass fraction, and burned mass fraction,
permitted an estimate to be made of the amount of unburned mass contained
inside the inflamed region during the combustion process. Thus, information
regarding the structure of the flame, values for the characteristic burning
time of unburned mixture within the flame, and a flame stretch factor, could
be estimated. The key results in each of these areas will now be reviewed.

From the measured cylinder pressure versus crank angle data, the measured
inlet mass flow rates, and an estimate of the residual burned fraction and the
heat losses to the combustion chamber walls, the mass fraction burned as a
function of crank angle throughout the combustion process can be obtained
from the energy conservation equation for the combustion chamber. This
analysis was carried out for all the pressure data available—about 10 conse-
cutive cycles at each of six different engine operating condition. An
empirical burning law was developed to fit this mass fraction burned data
set. An advantage of the new burning law compared to previous empirical
burning laws is that it applies for both the ignition delay and for the
developed flame propagation phases of combustion, in contrast to previous
laws where these two phases are treated separately. The new law is thus

consistent with developing theories of flame propagation in engines which indicate that the same mechanisms should govern both ignition delay and fully developed burning periods.

The geometric analysis of the photographic data on flame front location was carried out as follows. A best (least squares) circle was fitted to each photograph of the flame front profile, using as free parameters the radius of the circle and the position of its center. In the third dimension (parallel to the cylinder axis) it was assumed that the apparent flame center maintains the same relative distance between the cylinder head and piston crown as the spark plug at the time of spark. Consistency checks of these assumptions indicated they were reasonable and not critical to the subsequent analysis. From this geometric data, the volume of the inflamed region (the region contained behind the front of the flame), the area of the flame front, and the average normal speed of the flame front throughout the combustion process were determined.

The coupling of the mass fraction burned data and the flame geometric data allowed more fundamental quantities to be determined. By determining the unburned mass ahead of the flame from the volume of the unburned region, the rate of mass entrainment into the flame was calculated. The entrainment speed, the speed at which fresh mixture crosses the flame front, could then be determined as a function of time. It was shown that this entrainment speed increased rapidly to about 10 m/s as the first 5-10 percent of charge was burned and then remained essentially constant. The magnitude of the entrainment speed was shown to scale with engine speed, though there was considerable scatter in the data and the range of speed covered in these experiments was only 970-1230 rev/min.

A comparison of the mass inflamed (mass contained behind the flame front) and mass fraction burnt, and of the mass entrainment and mass burning rates, during the engine combustion process, showed that a significant amount of unburned mass is contained within the inflamed region (for example, for the average cycle when the inflammed mass fraction is 0.6, the burned mass fraction is 0.3). It was shown that the entrainment and burning processes are decoupled, and that thin flame assumptions cannot incorporate this exper- imental evidence. The flame is "thick"; within a zone behind the flame front of considerable extent, there exists both unburned, burned and reacting mixture.

The data was then used to determine a characteristic burning time. This burning time was defined as the characteristic lifetime of an unburnt fluid particle in the inflamed region. It was shown that this characteristic burn- ing time is of order 1 ms which, after an initial increase, shows a steady decreasing trend through the combustion process. This characteristic burning time provides an indication of the turbulent flame thickness, the order of 1 cm.

Finally, a flame stretch factor was defined and determined. An equi- valent laminar flame front area can be defined by equating the product of laminar flame speed, equivalent laminar flame front area and unburnt mixture density to the mass burning rate. Determination of this flame stretch factor showed that it increased from a value of 1.5 to 2.0 during the early stages of combustion to of order 10-15 during the fully developed burning stage.

To sum up, this part of the research supported by this grant has provided valuable insights into the propagation process and structure of turbulent flames found in spark ignition engines. It has been shown that the flame is thick, that the entrainment and burning process can be decoupled, and

that within this thick flame there exists substantial unburnt mixture.
It is clear that thin flame front models cannot fit this experimentally
derived information. This data base and these methods of analysis provide
valuable information for the further development of a turbulent flame pro-
pagation models.

3. CYCLE SIMULATION STUDIES OF THE EFFECTS OF TURBOCHARGING AND HEAT
   TRANSFER

The objective of this activity was to examine the effect of turbocharging
and variations in heat transfer on engine power, efficiency and NO_x emissions,
using an existing computer simulation of the spark-ignition engine operating
cycle.

A computer simulation had been previously developed which predicts the
efficiency, performance and nitric oxide emissions of a spark-ignition engine.*
With support from this NASA grant program, the computer simulation has been
used to (i) evaluate predictions of wide-open-throttle engine operation
against experimental data; (ii) carry out a comparison of the efficiency and
NO_x emissions characteristics of a naturally aspirated and a turbocharged
engine of equal performance; (iii) explore the effects of changes in heat
transfer to the combustion chamber walls, and the use of ceramics, on engine
operating conditions.

---

*See Heywood, J.B., Higgins, J.M., Watts, P.A. and Tabaczynski, R.J.,
"Development and Use of a Cycle Simulation to Predict SI Engine Efficiency
and NO_x Emissions", SAE paper 79021.

Predictions of the model for wide-open-throttle and turbocharged operation were verified through comparison with manufacturers' engine performance data. A 5.7ℓ naturally aspirated and 3.8ℓ turbocharged and naturally aspirated engines were chosen for this study. A comparison was made between measured and predicted brake mean effective pressure and brake specific fuel consumption. It was found necessary to allow for varying burn rates, and varying carburetor fuel-air metering characteristics over the engine speed range, to obtain reasonable agreement between performance predictions and measurements. Allowance also has to be made for blow-by and quenching, and cylinder-to-cylinder air-fuel ratio nonuniformities to obtain acceptable agreement for fuel consumption. The airflow into the engine in this cycle simulation was computed using quasi-steady one-dimensional flow equations. This study did not indicate that additional dynamic effects at high speed had to be incorporated to obtain acceptable predictions of airflow rate over the complete engine speed range.

A series of studies to compare a naturally aspirated and turbocharged engine with the same maximum power, at part load, at selected engine speeds was carried out. Use of the simulation permitted all other variables for the two engines to be held constant to isolate the effects of turbocharging alone. Under the above conditions, turbocharging significantly improves the efficiency of a spark ignition engine over most of the load range. The improvement is the order 10 percent for engines of the same maximum power. However, brake specific nitric oxide emissions are slightly higher for the turbocharged engine than for the naturally aspirated engines.

In the final area studied, the simulation was used to examine the effect of heat transfer reduction on engine operating characteristics at part-load and wide-open-throttle.

Heat transfer prediction formulas used in engine simulations are empirical approximations which have not been subject to extensive evaluation. Thus, the first study carried out examined the effect of an increase and decrease in heat transfer on engine operation to define the impact of pre-diction uncertainty, and to explore the effect of changes in heat transfer due to changes in flow velocities or combustion chamber surface area, with cold metal walls. The effects on cycle parameters such as power, efficiency and NO_x emissions are modest: e.g., a 25 percent change in heat transfer results in a 3 percent change in brake thermal efficiency, and a 4 percent change in brake power.

The impact of ceramic engine components on engine operation was then examined. The simulation was used at two compression ratios, 8:1 and 16:1, to produce results relevant to spark-ignition, stratified charge and diesel engine technology. Ceramic components (piston, cylinder, cylinder head, etc.) were added one by one. Different ceramic wall structures which produce significantly different ceramic temperatures were examined. The following conclusions emerged from these studies.

Unless the ceramic material is thermally insulated from any conventional metal support or coolant system, the increase in ceramic surface temperature above conventional metal wall temperatures is small, and the effect on engine operation is modest. Increasing the surface temperature of the ceramic material over the range 400 to 1200 K significantly reduces the engine heat transfer and raises the exhaust temperature. However, brake power is sub-stantially reduced due to the decreasing volumetric efficiency, and the brake thermal efficiency remains essentially constant. At part-load, the brake specific fuel consumption decreases slightly as the ceramic wall tem-perature is increased. At compression ratios typical of diesel operation,

the deleterious effects of reduced volumetric efficiency and power due to increased component temperatures are reduced. At compression ratios typical of spark-ignition engines, the effects of increased wall temperature on unburned mixture conditions (and hence on knock) would be substantial.

When ceramic components (piston, cylinder head, valves and cylinder liner) were added one at a time, it was shown that use of ceramic materials on the piston crown and cylinder head proved most effective in reducing heat transfer for simulated stratified charge or diesel conditions.

Thus, the predictions made with the cycle ; mulation indicate that changes in engine efficiency and performance may or may not be favorable depending upon the method employed to reduce heat loss. Decreasing the heat transfer coefficient while maintaining cool walls improves efficiency and performance. However, heat loss reduction by using ceramic cylinder components adversely affects engine power as a result of decreased volumetric efficiency, has little effect on efficiency, though it does significantly increase exhaust gas temperature.

4. APPENDIX: PUBLICATIONS COMPLETED ON THIS GRANT

Thesis

Watts, P.A., "Simulation Studies of the Effects of Lean Operation, Turbocharging and Heat Transfer on Spark-Ignition Engines", S.M. Thesis, Mechanical Engineering Department, M.I.T., May, 1979.

> A computer simulation is presented that predicts the efficiency, performance and nitric oxide emissions of a spark-ignition engine. Predictions of the model for wide-open-throttle and turbocharged operation were verified through comparison with manufacturers' engine performance data. Simulation studies were performed to determine the effects of lean operation, turbocharging and heat transfer on the efficiency, performance and nitric oxide emissions of a spark-ignition engine. The 5.7ℓ naturally aspirated and 3.8ℓ turbocharged and naturally aspirated engines were chosen for this study.

The cycle simulation studies of lean operation showed that the improvements in fuel consumption were the same for air and EGR at equal levels of mixture dilution. EGR, at the same dilution level as with air, produces much greater reduction in specific NO emissions. Further studies revealed that turbocharging significantly improves the efficiency and performance of a spark-ignition engine. However, the bsNO emissions are higher for a turbocharged engine. Heat transfer reduction studies indicated that the changes in engine efficiency and performance may or may not be favorable depending upon the method employed to reduce heat loss. Increasing the thermal boundary layer resistance significantly improves efficiency and performance, where as heat loss reduction by using ceramic cylinder components adversely affects power as a result of decreased volumetric efficiency. It is anticipated that heat loss reduction through utilization of ceramic engine components coupled with a turbocharger may provide a feasible method to significantly improve the efficiency and performance of spark-ignition engines.

Beretta, G.P., "Thermodynamic Analysis of Turbulent Combustion in a Spark-Ignition Engine. Experimental Evidence and Analytical Methods", S.M. Thesis, Mechanical Engineering Department, M.I.T., January, 1980.

PART I. A thermodynamic method to analyse fundamental turbulent flame information from cylinder pressure measurements and high-speed flame photography in a transparent-piston spark-ignition engine has been developed and applied. The method is independent of physical models of turbulent flame propagation. Entrainment speed u_e, inflamed and burnt mass fractions x_f and x_b, entrainment and burning rates $\dot{x}_f$ and $\dot{x}_b$ and a characteristic burning time τ are defined and estimated during the combustion period of an engine operating cycle.

The major results are that u_e remains approximately constant and a substantial fraction of the inflamed mass is unburnt. Information is extracted also on cycle-to-cycle variations.

An important use of the experimental evidence presented is to verify the assumptions of turbulent combustion models.

PART II. An analytical solution of the energy and entropy thermodynamic balance equations in the combustion chamber of a spark-ignition engine is presented with emphasis laid upon the required assumptions. The further assumptions needed to obtain approximate expressions of common use in research experiments, such as the pV^γ approximation, are discussed. An explicit method for estimating the mass fraction burnt given a cylinder pressure trace is also suggested. It is anticipated that the analysis presented will be useful for the interpretation of experimental data and the so-called second law or availability analysis of internal combustion.

Papers

Watts, P.A. and Heywood, J.B., "Simulation Studies of the Effects of Turbo-charging and Reduced Heat Transfer on Spark-Ignition Engine Operation", SAE paper 800289, presented at SAE Congress and Exposition, Detroit, MI, February 25-29, 1980.

A computer simulation of the four-stroke spark-ignition engine cycle has been used to examine the effects of turbocharging and reduced heat transfer on engine performance, efficiency and NO_x emissions. The simulation computes the flows into and out of the engine, calculates the changes in thermodynamic properties and composition of the unburned and burned gas mixtures within the cylinder through the engine cycle due to work, heat and mass transfers, and follows the kinetics of NO formation and decomposition in the burned gas. The combustion process is specified as an input to the program through use of a normalized rate of mass burning profile. For this information, the simulation computes engine power, fuel consumption and NO_x emissions.

Wide-open-throttle predictions made with the simulation were compared with experimental data from a 5.7ℓ naturally-aspirated and a 3.8ℓ turbocharged production engine. The predicted trends of mean effective pressure and fuel consumption showed acceptable agreement with the data.

Simulation studies were performed to compare the fuel consumption and NO_x emissions of a 5.7ℓ naturally aspirated engine with a 3.8ℓ turbocharged engine over the complete load and speed range. These engines have equal maximum power. Further studies were carried out to examine the effects of reduced heat transfer on engine performance, efficiency and NO_x emissions. Reductions in heat transfer were simulated by increasing the thermal boundary layer resistance, and through the use of ceramic materials on selected engine components over a range of combustion chamber wall temperatures.

Beretta, G.P., Rashidi, M. and Keck, J.C., "Thermodynamic Analysis of Turbulent Combustion in a Spark-Ignition Engine. Experimental Evidence", Paper No. WSS 80-20, presented at the 1980 Spring Meeting, Western States Section, The Combustion Institute, University of California, Irvine, CA, April 21-22, 1980.

A method independent of physical modeling assumptions is presented to analyze high-speed flame photography and cylinder pressure measurements from a transparent-piston spark-ignition research engine. The method involves defining characteristic quantities of the phenomena of flame propagation and combustion, and estimating their values from the experimental information. Using only the pressure information, the mass fraction curves are examined. A new empirical burning law is presented which well simulates such curves. Statistical data for the characteristic delay and burning anges show that cycle-to-cycle fractional variations are of the same order of magnitude for both angles (about 20 percent). Using only the photographic information on flame front contours, statistics are obtained for the apparent true ignition delay time. Enflamed volume, area of the flame front and an average normal flame front speed are estimated as a function of time. From the combined analysis of cylinder pressure history and flame photography the entrainment speed u_e (often called turbulent flame speed) is estimated and found to increase rapidly during the initial period of flame propagation. At a later time, when the mass fraction burnt is greater than about five percent, u_e remains approximately constant at a value of the order of 10 m/s for the present operating conditions with cyclic fractional variations of about 20 percent. Comparison of the enflamed and burnt mass fractions indicates that a substantial amount of unburnt mass is inside the enflamed region during flame propagation. Comparison of the rates of entrainment and burning shows that the two processes are not coupled as it is implied when a thin flame is assumed. The characteristic burning time is found to be of the order of 1 ms and tends to decrease through the combustion period. The flame stretch factor is also estimated. The present work concentrates on experimental evidence which can be used to test theoretical models and computer simulations of the phenomenon.