Internal Combustion Engine Combustion Chamber Process Studies at NASA Lewis Research Center

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Internal combustion engine studies can be divided into two categories, macroscopic studies and microscopic studies. Macroscopic studies include thermodynamic simulations and "averaged" measurements such as speed, torque, average exhaust temperature, etc. Microscopic studies include multi-dimensional models and detailed local measurements of in-cylinder gas velocities, temperatures, species concentrations, flow characteristics, etc. This paper describes the in-cylinder process studies underway at NASA Lewis Research Center which uses both of these methods.

Introduction

INTERNAL combustion engine optimization has been under way for well over a hundred years. It has not been until the last ten years that tools have been available to perform the in-situ studies necessary to gain a fundamental understanding of the processes occurring in the engines of interest. Two devices that have reached the level of refinement necessary to study the processes occurring in these engines during combustion are the laser and the high-speed digital computer.

Understanding the fundamental details of airflow and fuel pyrolysis in an internal combustion engine will lead to the development of engines with high efficiency, long life, and good power-to-weight ratio. Designs optimized for manufacturing economy can also be considered, once suitable predictive codes have been developed. This paper describes the research effort under way in the Intermittent Combustion Engine Branch at NASA Lewis Research Center for understanding the combustion processes occurring in these engines.

Intermittent Combustion Engine Branch Basic Research

The in-cylinder process studies under way in the Intermittent Combustion Engine Branch are based on an analysis approach which combines numerical simulations with detailed experimental studies. In general, since numerical simulations can be developed on nearly any computational machine and are readily transported from one location to another, these efforts have been conducted via grants. In our experience, the success of an experimental buildup required for combustion chamber process studies is very sensitive to personnel changes. Also, the experimental apparatus generally requires several part-time support people. The Intermittent Combustion Engine Branch has chosen to perform this type of work at NASA Lewis Research Center, with some exceptions.

Although not discussed in this report, the Intermittent Combustion Engine Branch is also supporting stress analysis studies for rotary and piston engines, high-temperature material studies, and fuel-injection and engine controls work. Many of these efforts will produce important engine design information during the current year.

The above studies briefly mentioned, and the in-cylinder process studies about to be described, are designed to give a good understanding of the factors that influence the weight, performance, and reliability of the engines of interest. These studies are designed in such a way that information from one experiment or simulation is used as initial or boundary conditions for another. The ultimate goal of this work is the development of a new class of light aircraft engines capable of delivering 1.5 hp/lb (0.5 kW/kg) with a brake specific fuel consumption of 0.30 lbm/hp/h (182 g/kW/h).

The details of the cylinder process research studies are now given.

Laser Velocimetry Studies

In order to understand how fuel and air are burned in an internal combustion engine, it is first necessary to be able to understand the air motion. For flow studies in a piston-cylinder configuration, except for the clearance volume region, a nonintrusive technique is almost mandatory for measurement of these flows. The laser Doppler velocimeter (LDV) is the ideal tool to make point measurements in this configuration. LDV studies have been conducted at Lewis Research Center to quantify the flow in a piston-cylinder configuration.[1] Results to date indicate that one must operate the system in forward scatter to obtain the signal-to-noise ratios necessary for repeatable down-mixed measurements. To quantify turbulence levels according to classical definitions, cycle resolved information is necessary.

Our solution to this problem is to devise LDV configurations that will give data rates sufficient to follow the variations in the flow during a period of interest. In addition, a flow visualization/measurement scheme that will give planar flowfield information is now being tested.

Holographic Optical Systems for Laser Velocimetry

Recent work[2] has shown that multifaceted holographic optical elements can be used to correct aberrations introduced into the optical system of a laser Doppler velocimeter by a nonflat window. For this experiment, three green beams, each separated by 41.25 mm in the vertical plane, and two blue beams, separated by 82.50 mm in a horizontal plane, are brought into coincident focus inside a plexiglass cylinder. The focal power to bring these beams to a common focus and the aberration correction required by the presence of the cylinder were built into the holographic elements. The principle demonstrated using the elements described is applicable for an arbitrary window geometry. Experiments have shown that this technique is viable for thick materials of high refractive index.[3,4]

Rotary Combustion Engine Seal Dynamics

Seal leakage and high seal friction have been cited as factors causing poor fuel economy in the rotary combustion engine

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(RCE). In order to examine rotary seal dynamics, a cooperative effort between researchers at Michigan Technological University and the Intermittent Combustion Engine Branch at Lewis Research Center was initiated and the initial phase completed. The results of this study included the development of a code that predicts RCE seal dynamics.[5]

Real-time work cell pressures are incorporated into a dynamic analysis of the gas sealing grid in a rotary combustion engine. The analysis, which utilizes only first principle concepts, accounts for apex seal separation between the sides of its restraining channel and apex seal rotation within the restraining channel. The results predict that apex seals do separate from the trochoidal bore and shift between the sides of their channels. They also show that these two motions are regularly initiated by a seal rotation. The predicted motion of the apex seals is similar to the experimental results. Frictional losses associated with the sealing grid are also calculated and compare well with measurements obtained in a similar engine. A comparison of frictional losses for various sealing configurations was made. This comparison included steel vs carbon apex seals, as well as friction losses for single and dual side sealing.

The most interesting aspect of this study showed that the friction losses due to the side seals are of the same order of magnitude and possibly larger than apex seal frictional losses.

The next step is to combine this simulation with the thermodynamic model to produce a more realistic picture of the effects of RCE seal leakage and friction.

Jet Ignition Using Liquid Fuels

High-temperature fuel jet combustion studies have been under way at the University of California—Berkeley over the past four years.[6,7] The prime motivation of this work was to determine under what conditions preheating of the fuel offers a significant combustion rate controlling mechanism not now available. It was hypothesized that if ignition delay can be controlled by preheating a fuel, engines could operate at very high efficiencies regardless of the quality of the fuel.

To examine this concept, a high-pressure bomb and furnace were constructed to study the combustion of *n*-dodecane and *n*-heptane, the major components of diesel fuel. This study was conducted at supercritical conditions. The furnace and bomb were fitted with windows for optical access and the appropriate pressure transducers and thermocouples to monitor the experiment. Fuel was supplied to the preheated bomb by a modified Roosa-Master fuel injector suitable for operation at high temperatures. This apparatus is capable of maintaining pressures of 21 atm at 800 K within the bomb, the injected fuel being at the same temperature.

Concurrently, the Berkeley group developed a technique for the determination of pure hydrocarbon properties below, at, and above the critical point. Results of this study[6,7] indicate that preheating the fuel prior to injection does decrease the induction time. This decrease is mainly a function of temperature and not pressure in the combustion chamber. As temperatures are increased above 700 K, the combustion rate effects due to transport phenomena become more significant.

Numerical Study of Flowfields in a Motored Four-Stroke Piston-Cylinder Configuration

An indispensable part of understanding combustion in an engine is understanding the airflow in the combustion chamber. As a first step toward being able to predict the velocity fields and turbulence levels in a multivalve engine where three-dimensional effects are very important, we have chosen to model an axisymmetric piston-cylinder configuration. The two-dimensional model that has been under development on grant[8] has many of the essential features of three-dimensional models. Measurements can be made for model validation in an axisymmetric piston-cylinder configuration where the dominant features of the flow are believed to be two-dimensional.

Results of this simulation have been published[9] and are now briefly described.

The effects of the compression ratio, engine speed, bore-to-stroke ratio, and air intake flow angle on the turbulent flowfield within an axisymmetric piston-cylinder configuration have been investigated numerically by means of a finite difference procedure that solves the conservation equations of mass, momentum, and energy. Turbulence has been modeled by means of a two-equation model for the turbulent kinetic energy and the dissipation rate of turbulent kinetic energy. The motion of the piston has been accounted for by introducing a mapping which transforms the moving boundary problem associated with the piston motion into a fixed boundary problem. The valve motion within the cylinder has been analyzed by defining a fixed grid in which the valve can move in such a way that its profile corresponds to that of an intake/exhaust valve in a four-stroke engine. The numerical results show that the flowfield is sensitive to the engine geometry and very sensitive to the valve seat angle. Higher compression ratios produce higher rms velocity values within the cylinder. For an air intake flow angle of 45 deg, the flowfield within the cylinder shows three elongated vortices formed during intake, which persist into the compression stroke. These vortices break up and merge in the compression stroke. Other vortical structures are formed and persist into the expansion stroke. For an air intake angle of 0 deg, the flowfield consists of two vortices which disappear by the end of the compression stroke. The effects of the bore-to-stroke ratio on the flowfield indicate that for the long strokes, high levels of turbulent kinetic energy are present within the cylinder. These turbulence levels are very sensitive to the geometry of the system of interest.

The numerical results also indicate that the velocity field and turbulent kinetic energy field prior to top-dead-center (TDC) are very sensitive to the air intake flow angle and the bore-to-stroke ratio. These parameters play an important role in determining the engine combustion efficiency, heat losses, and pollutant formation.

Currently, this code is being developed to study the performance of an axisymmetric, two-stroke, fuel-injection diesel engine.

Thermodynamic Modeling of Rotary Combustion Engines

The stratified-charge rotary engine has the potential to be a competitive choice as a future power plant for light aircraft.[10] To gain better insight into the operation of this engine, a thermodynamic model is being developed under grant[11] to study and predict engine performance, emissions, and fuel economy.

An existing piston engine simulation was modified[12] to accommodate the rotary engine geometry for preliminary performance and sizing calculations. This simulation employs a homogeneous charge spark-ignition combustion model, which includes a prespecified fuel rate burning model. In addition to change in geometry, a crevice volume and leakage model were added to the simulation. Motoring RCE data were used to calibrate the model. A parametric study for light loads showed that gas leakage is the predominant effect on engine performance. At light loads, crevice volumes and heat transfer had little effect; however, these are expected to become more important at high speeds and loads.

Recent work on this thermodynamic model has been focused on the development of a stratified-charge combustion model. Heat release will be calculated from pressure-crank angle data. Thermodynamic property analysis, heat transfer, crevice, and leakage submodels are also included in the formulation of this model.

Detailed combustion chamber pressure and performance data are now being obtained[13] for the stratified-charge rotary engines of interest. When this data are analyzed using this model, a better understanding of the processes occurring within the RCE will be obtained.

Multidimensional Rotary Combustion Engine Codes

A numerical study of the fluid flow, heat transfer, and combustion processes inside the combustion chambers of a direct-injection, stratified-charge rotary engine has been undertaken.

Under NASA grant,[14] efforts are presently under way at the University of Florida to develop two numerical codes for studying the fluid mechanics, the heat transfer, and the combustion that occur within the rotary engine combustion chambers. One of the numerical codes (two-dimensional code) is for studying an idealized two-dimensional rotary engine. The other numerical code (three-dimensional code) is for studying a more realistic three-dimensional rotary engine. Progress made in the development of these two codes is described below.

The two-dimensional code is based on the numerical solutions of the ensemble-averaged conservation equations of mass, species, radial momentum, azimuthal momentum, and thermal energy. The ensemble-averaged conservation equations were closed by the K-ϵ model of turbulence, which was modified to account for some of the effects of streamline curvature and compressibility.

To obtain numerical solutions to the conservation equations described above, the continuous domain inside one of the combustion chambers of the rotary engine was represented by a grid system. The grid system was generated by an algebraic grid-generation technique. It moves and deforms with the combustion chamber as the combustion chamber moves with the rotor. The conservation equations were first transformed to a moving coordinate system corresponding to the motion of the grid system and were then expressed in finite difference form.

At the present time, various boundary conditions for the intake, exhaust, and fuel-injection ports are still being tested for accuracy and numerical stability. With the intake, exhaust, and fuel-injection ports closed, numerical experiments conducted so far have indicated that the numerical solutions generated by the two-dimensional code were stable and physically reasonable if the Courant number was kept below 60.

The three-dimensional code is based on the two-dimensional code with the following modifications:

1) The ensemble-averaged axial momentum equation is added to the conservation equation employed in the two-dimensional code.

2) All the conservation equations described previously are generalized to include three spatial coordinates.

3) The ensemble-averaged conservation equations for the three-dimensional code are closed by an algebraic stress equation model of turbulence instead of the K-ϵ model of turbulence.

The development of the three-dimensional code is still in the programming stage.

Summary

The goal of developing a highly efficient, lightweight aircraft engine will be achieved only by a concerted program composed of practical engine studies and experiments, within which the results of basic research can be applied. As part of that program, the Intermittent Combustion Engine Branch at NASA Lewis Research Center has under way research whose objective is to understand the internal processes that occur in rotary and piston engines. This work involves both numerical simulations and detailed experimental studies. The emphasis of this basic research effort is to gain a fundamental understanding of the important processes affecting combustion in piston and rotary engines.

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