HC QUENCH LAYER FORMATION
IN COMBUSTION PROCESSES

TECHNICAL PROGRESS REPORT
FOR THE PERIOD
Sept-Dec. 1979

MASTER

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INTRODUCTION

The project is aimed at understanding wall quenching and other processes responsible for surface generated hydrocarbons in combustion under engine-like conditions. The study will focus on the effects which turbulence has on the evolution of hydrocarbons. At the conclusion of the program, significant new experimental information will have been generated and an analytical model of the fluid mechanics and some aspects of the chemistry of quenching will be formulated.

The work is divided into three tasks: (I) combustion bomb experiments at Ford to measure the effect of turbulence on the chemical species near the cold surface, (II) combustion bomb experiments at U. of M., using a similar turbulence generating device, to fully characterize the flow and turbulence in the vicinity of the quenching surface, and (III) an analytical study, also at U. of M., to characterize fluid mechanical scales of interest in the boundary layer and to find an analytical solution to describe the evolution of the layer.

This report covers the work performed from September to December 1979 and will include a discussion of current technical status, and plans for the next major reporting period, January-April 1980.

TECHNICAL STATUS

The major accomplishments to date are (i) demonstration of the feasibility of single shot sampling valve operation and gas analysis in the Ford bomb under laminar combustion conditions, (ii) formulation of design rationale for turbulence generation scheme and bomb geometry, and (iii) formulation of an approach to modeling turbulent boundary layer conditions.

A detailed discussion of these items follows:

Task I - Sampling Valve Measurements (Ford)

The Ford Electrohydraulic Sampling Valve has been set up in a spherical bomb to demonstrate the feasibility of extracting gas samples from the wall layer on a single shot basis and of determining the chemical composition of such samples. The experimental arrangement is shown in Figure 1. The valve which is described in detail in ref (1), is electronically triggered and controlled by means of a servo valve which controls the hydraulic pressure on a piston to actuate the valve. This design permits the flexibility of triggering and control inherent in electronic devices while at the same time maintaining the speed and force characteristic of hydraulic actuation which gives the valve fast time response and low leakage. The valve is outwardly opening (into the bomb) and is of a flush design so that when closed it presents negligible disturbance to the wall layer.

During the preliminary study, the bomb was not equipped for turbulence generation so that the flame propagated in a laminar fashion from the spark plug toward the valve. At a predetermined time interval after ignition, the valve was triggered and a sample of gas withdrawn into a previously evacuated manifold. Sample size was determined by the measured pressure in the manifold and the known manifold volume. Sample size was on the order of 1.5 cm³ at STP which corresponds to a sample thickness of ≈ 3 mm in the bomb. The sample manifold is directly connected to a gas chromatograph which is used to analyze the gas for C₁-C₃ hydrocarbons, and CO, CO₂, O₂, N₂, species which are appropriate to the propane-air gas mixture used. By making a series of bomb firings and sampling at various time intervals from ignition, a time history of the material in the wall layer can be built up. No major difficulties were encountered with the technique. The data obtained is limited in quantity, however, it is being analyzed and will be used to compare with baseline laminar data to be obtained in the cylindrical bomb when it is equipped with a turbulence device.

Task II - Flow Studies (U-M)

Design Rationale of Turbulence Generation Scheme

The program objectives are to study the effects of turbulence on the amount of residual hydrocarbons in the quench layer in a combustion bomb system that simulates the combustion process of an internal combustion engine. We have chosen to generate the turbulence in the bomb by means of the intake flow process, in particular by means of swirl and in some cases a turbulence grid.

The bomb shown in Fig. 2, is in the form of a cylinder with optical windows at both ends to permit schlieren photographs and laser velocimeter measurements of the flow process. Flow enters the bomb from a radial port with the option to select various nozzles to deflect the flow and provide different

amounts of swirl and turbulence. High speed schlieren photographs will be used to obtain the overall pattern of the flow at various time intervals after injection and simultaneous hot wire measurements will be made at a location directly opposite the inlet nozzle where the sampling valve will be located. Various ignition locations will be used including central ignition (shown in figure) and edge ignition.

The different levels of turbulence and swirl will be controlled by the use of various injection pressures and nozzles, the insertion of a turbulence grid, and varying the time that the turbulence is allowed to decay before ignition of the charge. The use of a constant pressure tank between the main gas storage tank and the bomb allows constant inlet conditions for a large number of tests.

These test measurements will provide data on the flow characteristics that exist at the location where gas sampling measurements of the quench layer hydrocarbons will be made. Also, the simple swirl pattern provides a practical geometry for the analytical model.

Current Status

To date, the schlieren system has been assembled and is operating and all of the components for the cold flow studies are on hand except for the inlet solenoid valve. A supplier for the valve has been located and one will be obtained by January 15. The cold flow system is being assembled using the Ford bomb and should soon be in operation.

Task III - Analytical Study

It was originally proposed to consider quenching conditions for two general cases, one where the core flow outside the boundary layer has an average velocity of zero, (only a thermal boundary layer exists), and one where the average core velocity has an arbitrary nonzero value. Because the flows in both the cylinder of an I.C. engine and in the experimental apparatus (combustion bomb) have varying amounts of swirl, it appears that the latter problem is by far the more important and it is this one which is under consideration presently.

The present work is concerned with a simplified description of the quench phenomenon, in which no detailed reaction mechanisms are employed. It is assumed that swirl exists and that as the flame passes over the wall, there is a region of combustible mixture which does not react because of the heat transfer at the cool wall; i.e., the temperature in this region is too low to support reaction. Due to the very large gradients in the wall layer of a turbulent boundary layer, this quench distance must be of the order of the thickness of the wall layer. Hence, the first goal is to calculate the order of magnitude of the thickness of the wall layer. In this calculation, the flow is taken to be a hot core flow (at the temperature, density, pressure, and velocity of the burned gases in an I.C. engine cylinder or combustion bomb) over the cool wall. Since the ratio of the thickness of the boundary layer to the cylinder radius is so small, a flat plate boundary layer calculation suffices.

The core flow velocity is small compared to the speed of sound in the combustion chamber, but due to the heat transfer through the boundary layer, the density is variable; hence the solution is that for a low Mach number compressible flow boundary layer. Under the assumptions made, the Crocco integral may be used to relate the temperature and velocity distributions. A simple mixing length model for the eddy viscosity has been used in an analysis similar to that used by Van Driest (2) for a compressible high Mach number flow. The result is an equation for the velocity distribution, in terms of a corresponding incompressible flow profile, which may be used to find a relationship between the thickness of the boundary layer, the Reynolds number, and the friction velocity. A second equation is provided by a momentum integral relation now under study. Thus, for a prescribed Reynolds number it will be possible to calculate the corresponding boundary layer thickness and friction velocity. Finally, using an equation already derived, it will be possible to calculate the corresponding order of the thickness of the wall layer.

PLANS FOR NEXT PERIOD (January-April 1980)

By the end of the next period it is expected that the dynamic charging set ups to generate swirl and turbulence will be completed and installed in both the Ford and the U-M bombs. Hot wire data and schlieren photos of the cold flow induction process will have been obtained and will be used to guide the turbulent sampling valve experiments scheduled to begin at Ford sometime in April. It is also planned to begin LDV experiments at this time at the U-M.

In order to avoid duplication of effort and to obtain a consistent set of sampling and flow data, it was decided to time-share the Ford cylindrical bomb between Ford and U-M facilities. This bomb has relatively low crevice volumes and is more suitable for sampling valve operation. The U-M bomb which has large crevice volumes and a different aspect ratio will be used primarily to develop the LDV technique. Consequently, the Ford bomb is presently at the University of Michigan where cold flow turbulence data are to be obtained. After these initial measurements are completed, this bomb will then be returned to Ford for the gas sampling measurements under fired conditions. While this bomb is at Ford, the U-M bomb will be used at Ann Arbor to develop the LDV technique under single-shot firing conditions. When the LDV technique is fully operational the Ford bomb can again be moved to the U-M for final hot flow measurements.

During the next period in the analytical study, it is planned to use existing calculations for the core flow velocity distributions in engine cylinders with swirl, to establish a range of Reynolds numbers for the flow in such chambers. In addition, the boundary layer analysis will be completed. Finally, upper limit estimates of the fraction of fuel-air mixture not burned will be made based on the calculated sublayer thicknesses.

REFERENCES

1. LoRusso, J. A. Lavoie, G. A., and Kaiser, E. W., "An Electrohydraulic Gas Sampling Valve with Application to Hydrocarbon Emissions Studies," SAE paper 800045, presented at the SAE Automotive Congress, Detroit, Feb. 25-29, 1980.
2. Van Driest, E. R., "Turbulent Boundary Layer in Compressible Fluids," J. Aero. Sci., 18, 3, March 1951.

MILESTONE CHART: HC QUENCH LAYER FORMATION IN COMBUSTION PROCESSES

- I. SAMPLING VALVE MEASUREMENTS
 1. SET UP SAMPLING VALVE G.C. FOR SINGLE SHOT APPLICATION.
 2. DEVELOP TURBULENCE DEVICE
 3. S.V. MEASUREMENTS UNDER TURBULENT CONDITIONS.
- II. FLOW STUDIES
 1. DEVELOP TURBULENCE DEVICE
 2. COLD FLOW RUNS (HOT WIRE - SCHLIEREN)
 3. HOT FLOW RUNS (LDV)
- III. ANALYTICAL STUDY
 1. INVESTIGATE TURBULENCE SCALES
 2. DEVELOP ANALYTICAL SOLUTION

*INDICATES PERCENT OF TASK ACCOMPLISHED

12-31-79

Fig. 1. (a) Schematic of sampling valve feasibility experiments with the Ford spherical combustion bomb. (b) typical oscilloscope trace showing valve trigger, valve lift and bomb pressure as a function of time after ignition. Laminar combustion conditions.

Fig. 2. - Cylindrical combustion bomb design showing general swirling flows generated by intake system geometry and turbulence grid.