DOE/ET/15303-T5

MASTER

HC QUENCH LAYER FORMATION IN COMBUSTION PROCESSES

TECHNICAL PROGRESS REPORT

FOR THE PERIOD

May-Nov. 1980

Prepared for

U.S. Department of Energy

Albuquerque Operations Office

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by

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December 1980

CONTRACT NO. DE-AC 04-79ET-15303

DISCLAIMER

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 concerns the effects of turbulence 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 May to July 1980 on the original contract, and from August to November 1980 under a current no-cost extension. A final report will be submitted pending a decision on funding of a proposed extension to this contract.

TECHNICAL STATUS

Significant areas of progress during the reporting period are: (i) sampling valve data of wall-layer hydrocarbon concentrations have been obtained and analyzed for both laminar and turbulent flow conditions in the quench zone. Also, bulk gas samples of the exhaust emission were obtained and it was determined that at least 85% of the exhaust hydrocarbon emission in this reactor was coming from out-gassing of stored hydrocarbons in the dynamic charging system of the reactor, (ii) an improved streak schlieren system with high magnification has been developed for photographs of the quench and/or boundary layer and the cylindrical combustion bomb with optical access has been prepared for firing, and (iii) a simplified analysis of quench-layer thickness under turbulent flow conditions has been carried out and a model which includes diffusion and burnup in the boundary layer has been formulated.

A detailed discussion of these items follows:

Task I - Chemical Composition Probing of the Hydrocarbon Quench Layer (FORD)

Measurements of the wall-layer and bulk-gas hydrocarbon concentrations have been obtained in a cylindrical combustion bomb under initially quiescent conditions and with swirling-turbulent flows generated by the dynamic charging of the vessel. The apparatus is shown schematically in figure 1. It has a cylindrical internal shape with an 8.25 cm. diameter, an 8.25 cm. length and a volume of .44 liters. It contains a capacitive discharge spark, pressure transducer, a flush mounted Ford electro-hydraulic sampling valve (FEHSV)-- described in detail in the Sept.-Dec., 1979 progress report-- and a dynamic charging system. The dynamic charging system is described in the Jan.-Apr., 1980 progress report.

In a typical quiescent flow experiment, the combustion bomb is filled with propane-air at an equivalence ratio of 0.9 and allowed sufficient time for all gas motion due to the filling processes to dampen out. The mixture is then ignited and a small gas sample, approximately $1x10^{-4}$ gms, is captured in a 12 cm^3 previously evacuated manifold through the FEHSV at a pre-set time after ignition. In addition to this sample, a bulk gas sample is removed through the inlet valve into an evacuated pyrex container at either 5 or 10 minutes after ignition. These samples are injected into a gas chromatograph and analyzed for stable C_1-C_4 hydrocarbons, O_2, N_2, CO and CO_2.

In a typical swirling-turbulent flow experiment, the combustion bomb is initially filled with propane-air to 1 atmosphere pressure and the prechamber is filled to 6 atmospheres pressure. Upon initiation of the timing sequence, the solenoid filling control valve is opened for 80 msec. and allows the reactor to be filled to the firing pressure of 2 atm., with additional propane-air from the prechamber. At 100 msec. after induction, the gas in the reactor is ignited, and a gas sample withdrawn at a preset time after ignition. Bulk gas sampling and GC analysis procedures are the same as in the quiescent experiments.

Figure 2 shows the propane concentration -- fuel molecule -- and figure 3 shows the ethylene concentration -- typical intermediate species -- as a function of time relative to the time corresponding to peak pressure in the reactor. Sampling-valve data are presented for the case of a flame propagating into a quiescent mixture and the case in which the flame propagated into a swirling-turbulent flowfield. For these data, the velocity near the reactor wall was 20 m/sec. and the turbulence intensity was .8 m/sec., as determined by the flow measurements described in the Jan.-Apr., 1980 progress report.

For quiescent flame quenching, we observe that the propane concentration drops from its initial value of 10^5 ppm'C' to approximately 5 ppm'C' within 5 msec of flame arrival at the sampling valve. Under turbulent flow conditions, the propane concentration drops from 10^5ppm'C' to approximately 1 ppm'C' in the same time period, suggesting a stong effect of turbulence on wall quenching. However, at this time in our experimentation, it is difficult to attribute this difference in minimum propane level to the direct interaction of turbulence with the quenching process. This difference may also be due to the effect of the bulk gas motion on the detailed shape of the gas volume drawn into the sampling valve. Thus no firm conclusion can be made at this time as to the effect of turbulence on wall quenching. For both initial flow conditions, the propane concentration then rises from the minimum value to a final well mixed exhaust concentration (350 ppm'C') which is identical for the two cases within the experimental repeatability.

As represented by ethylene in figure 3, the intermediate species concentrations in the sampling region peak at a time in which the corresponding rate of consumption of fuel is at a maximum. The concentration then drops to below 10 ppm'C' within 30 msec. of flame arrival. In these experiments, the maximum amount of ethylene present in the gas sampled from the wall layer under quiescent flow conditions is identical to the maximum amount of ethylene sampled from the wall layer under turbulent flow conditions. Again to within experimental repeatability, the final well mixed exhaust values are eqivalent.

In addition to the sampling valve experiments, bulk-gas sampling experiments were conducted to determine the source of the majority of the exhaust hydrocarbon emission. In these experiments, the reactor was fired under quiescent flow conditions with and without the dynamic charging system connected to the reactor. With the charging system attached to the reactor, the exhaust hydrocarbon level was consistently 250-500 ppm'C'. Without the charging system attached to the reactor, the exhaust hydrocarbon emission was approximately 50 ppm'C'. This indicates that a significant fraction of the exhaust hydrocarbon level in the bomb and hence the secondary rise in the propane concentration in figure 2 is due to outgassing of crevice volumes in the charging system.

These experiments suggest that post-quenching diffusion and oxidation processes from open walls are fast enough that wall-quench hydrocarbons do not make a major contribution to the exhaust emissions in this reactor. The experiments also suggest that fluid motion parallel to the quenching surface and fluid motion with a low degree of turbulence, u'= 4%u, appear to reduce the minimum propane concentration in the wall layer from 5 to 1 ppm'C'. However, the cause of this difference is not well understood at this time and could be related to systematic changes in the sample volume shape due to the bulk fluid motion. In addition, for this particular reactor, it was shown that the exhaust hydrocarbon emission level was strongly influenced by crevice volumes in the dynamic charging system, and that these crevice stored hydrocarbons determine the exhaust hydrocarbon emission level.

Task II Characterization of the Turbulent Flow Field (The University of Michigan)

In our previous Technical Progress Report for January to April 1980 we presented results of a number of experimental measurements characterizing the cold flow pattern in the cylindrical Ford combustion bomb. Graphs were included to present our measurements of gas velocity, temperature, pressure, and turbulent fluctuation levels. We also included schlieren photographs of the density gradients and overall flow pattern. Since April we have improved the schlieren system to obtain color schlieren photographs; we have used several lens combinations to magnify the schlieren image for future photographs of the quench layer; we have written a computer program to analyze the velocity fluctuations recorded previously, and we have been making the combustion bomb operational for firing.

Two different types of photographic tests have been planned for the firing conditions. The first provides instantaneous schlieren photographs of the full bomb at various time delays following the spark and the second will obtain local magnified streak-schlieren photos of the flame as it approaches a quench surface. To prepare the bomb for these tests, we have added a premixing chamber, plumbing and instrumentation for preparing the combustible mixture; a spark plug with extended electrodes to locate the spark gap roughly at the bomb surface; required electronics and variable delay circuit for firing the delayed schlieren spark source and a separate strobe light to provide a timing mark on the photograph for proper phasing with other measurements. Additional modifications are being incorporated in the entire setup to insure operator safety in the event of a malfunction.

The schlieren system has been extensively modified and improved in the last two months. Black and white schlieren photos of the flow in the bomb were taken first; typical photos are shown in Fig. 4. The knife edge was then replaced with several types of color grids until an optimum quality color schlieren image of the flow pattern in the bomb was achieved. It was hoped that additional information could be gained from color photographs; however, it was concluded that this was not the case. The color images had less resolution than the very sharp black and white images; this is due to the sharper light cutoff provided by the knife edge as compared with the finite size color grid.

Modifications to the schlieren system which are necessary to set highly magnified streak-schlieren images of the quenching process were also undertaken. This involved testing several combinations of lenses

and lens apertures to set an acceptable image size of maximum brightness. Light intensity was also significantly improved by replacing the arc source by a laser and commercial beam expander.

At the present time, schlieren photographs of the flame propagating through the combustion bomb under quiescent initial conditions have been obtained. A series of six photographs representing different times in the combustion process is shown in Fig. 5. If the proposed extension to this project is funded, this technique will be applied to the turbulent combustion case.

Task III Analysis
(The University of Michigan)

An analysis has been made by means of which the first order approximation to the size of the quench layer on the wall of a combustion chamber can be calculated under certain conditions. Thus, the case where a turbulent swirl velocity exists has been considered, with Reynolds number, based on the swirl velocity at the chamber wall and on a length of roughly twice the cylinder circumference, greater than 10^4. The wall temperature is taken to be constant, and it is assumed that an ignition temperature can be defined for the fuel air mixture under consideration. The analysis in which no diffusion out of the quench layer is considered has been completed. Computer solutions have been obtained showing the variation of the quench layer thickness with each of the parameters involved. Comparison with available experiments indicates that the trends shown by the solution are correct, but that the calculated magnitude of the quench layer appears to be too large by a factor of roughly three. Therefore, it has been decided to assess the effects of diffusion out of the quench layer after the original reaction has ceased.

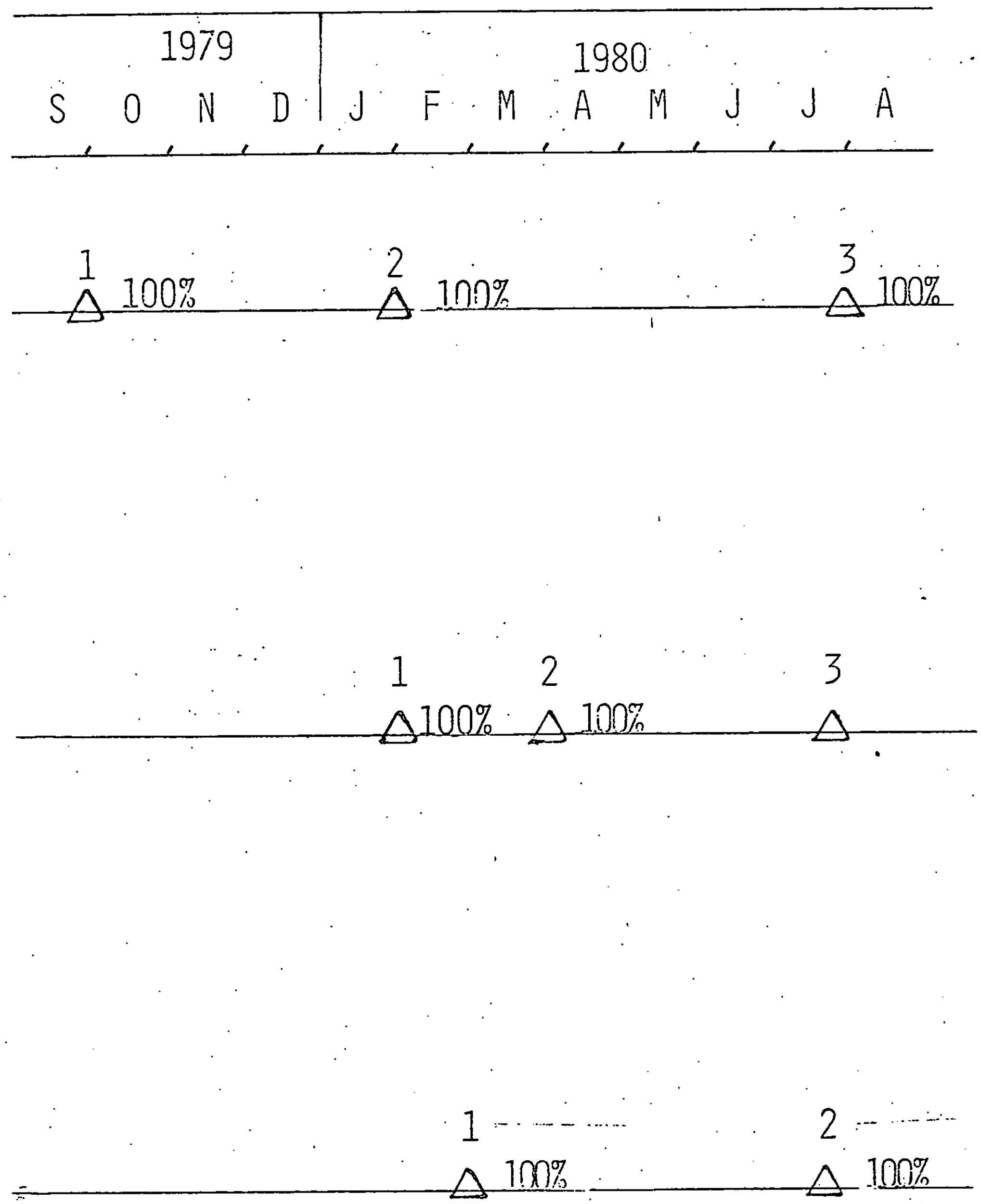
The problem formulation when diffusion is considered reduces to an unsteady diffusion flow. Actually, there are two unsteady processes taking place. First, because in an engine cylinder the pressure and temperature are decreasing as the piston recedes, the distance from the wall to the point at which the temperature reaches the ignition value changes with time. In addition, there is diffusion. However, the characteristic time associated with the change in the thickness of the layer under consideration is governed by the RPM of the engine and is large compared with the characteristic time associated with the diffusion process, the latter characteristic time being governed by the size of the quench layer. Moreover, it is large enough that unsteady terms need not be accounted for in the boundary layer analysis, to the order retained. In addition, it is assumed that the decrease in swirl velocity is negligible during the total time in question. Hence, the problem is quasi-steady insofar as the typical boundary layer conditions are concerned; these characteristics are calculated at any time as though the flow was steady at the given conditions, with unchanged swirl velocity.

Two components, burned and unburned gases, are considered at this stage of the analysis. It is assumed that the laminar and turbulent Schmidt numbers are unity and that thermal diffusion is negligible. The equation expressing the conservation of mass of the unburned gas thus reduces to a typical diffusion equation with an effective diffusion coefficient. The boundary conditions are such that at the wall the mass flow is zero and at the point where the ignition temperature is reached the concentration of unburned gas is zero.

An analytical solution has been obtained for the diffusion equations for conditions of a quasi-steady temperature profile and for the case in which the ignition temperature, T_{ig}, is within the linear portion of the boundary layer. The solutions show a significant amount of burnup under typical engine conditions.

Work is now underway to set up a numerical solution which will do away with the restriction on T_{ig}, and which will permit inclusion of a fuel source at the wall. If funding of the proposed extension is approved, this will be applied to the problem of burnup of hydrocarbons released from a wall oil film.

MILESTONE CHART: HC QUENCH LAYER FORMATION IN COMBUSTION PROCESSES



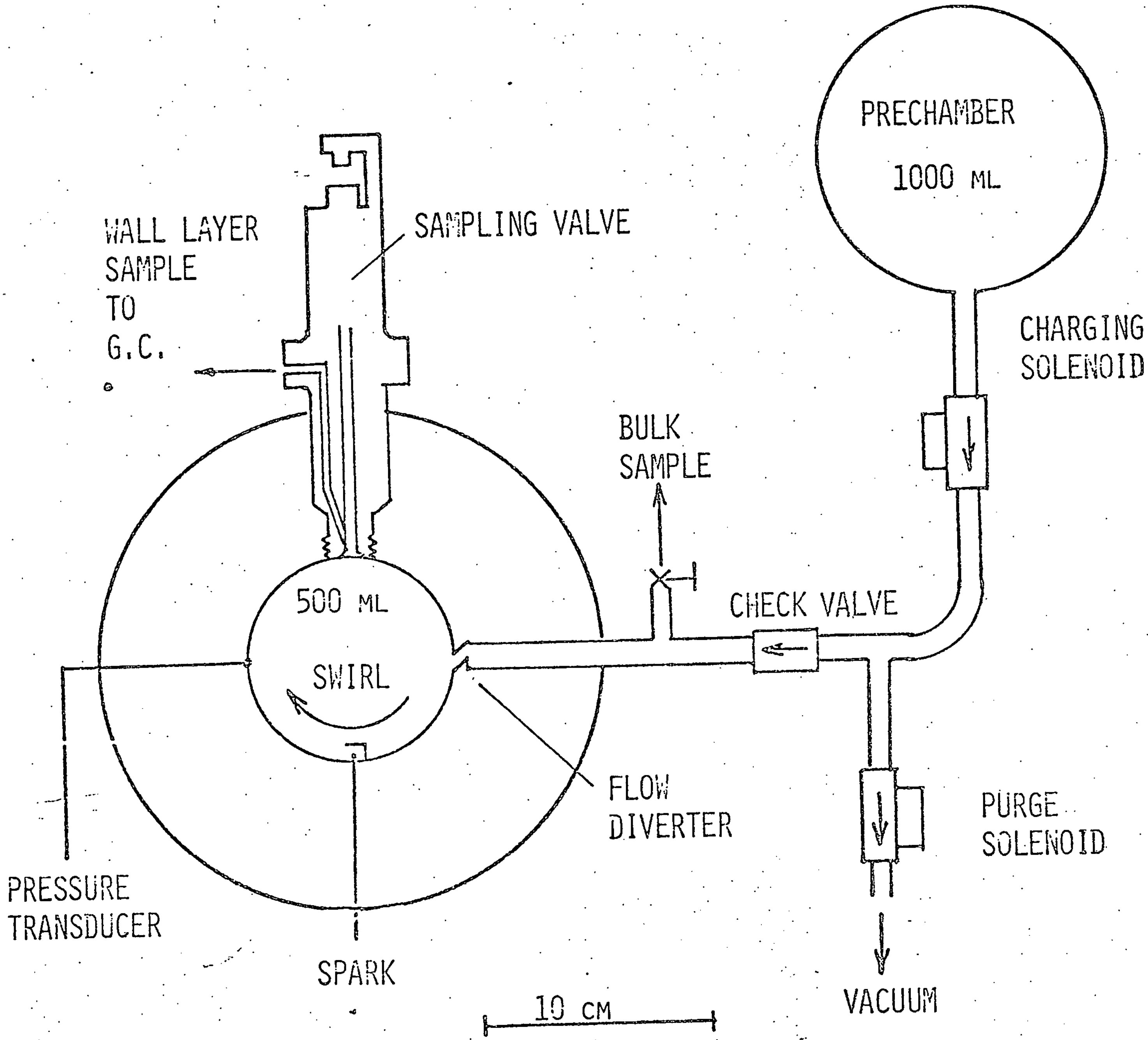
I. SAMPLING VALVE MEASUREMENTS
   1. SET UP SAMPLING VALVE G.C. FOR SINGLE SHOT APPLICATION.
   2. DEVELOP TURBULENCE DEVICE
   3. S.V. MEASUREMENTS UNDER TURBULENT CONDITIONS.

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

REV. 11-19-30



CYLINDRICAL COMBUSTION BOMB
WITH SWIRLING INLET FLOW

Figure 1.

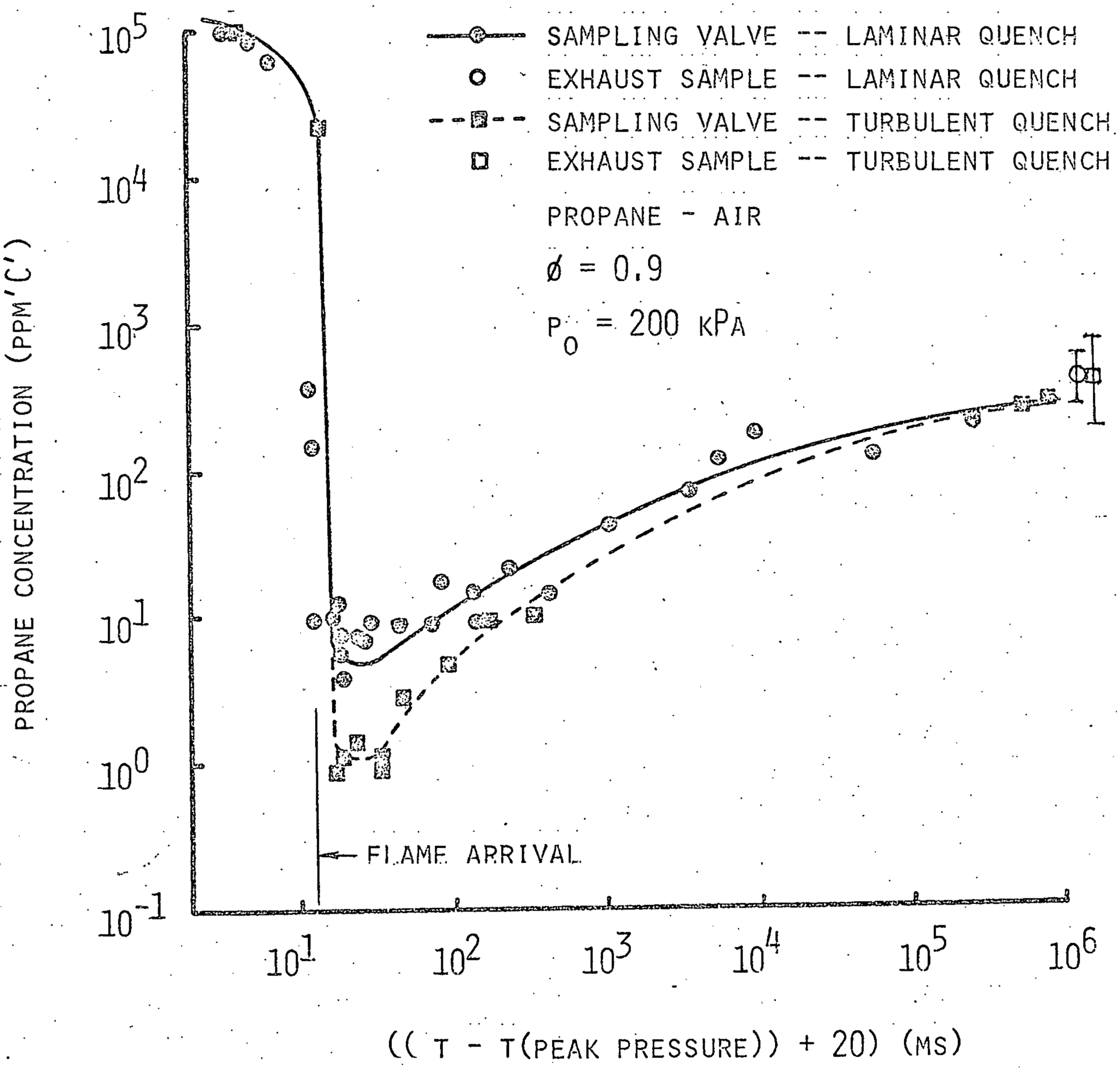


Figure 2. Propane concentration as a function of time for quenching under laminar and turbulent conditions.

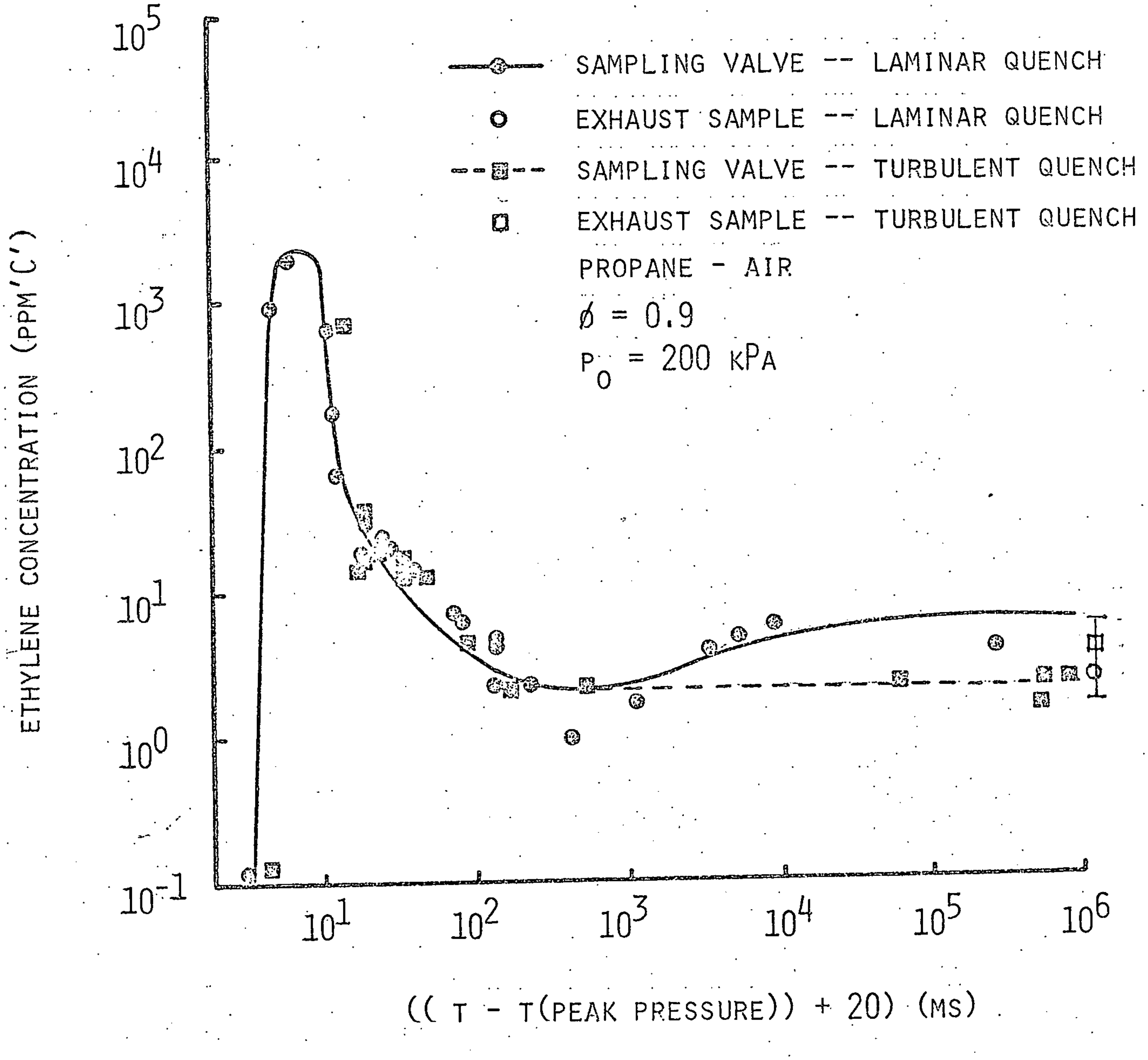
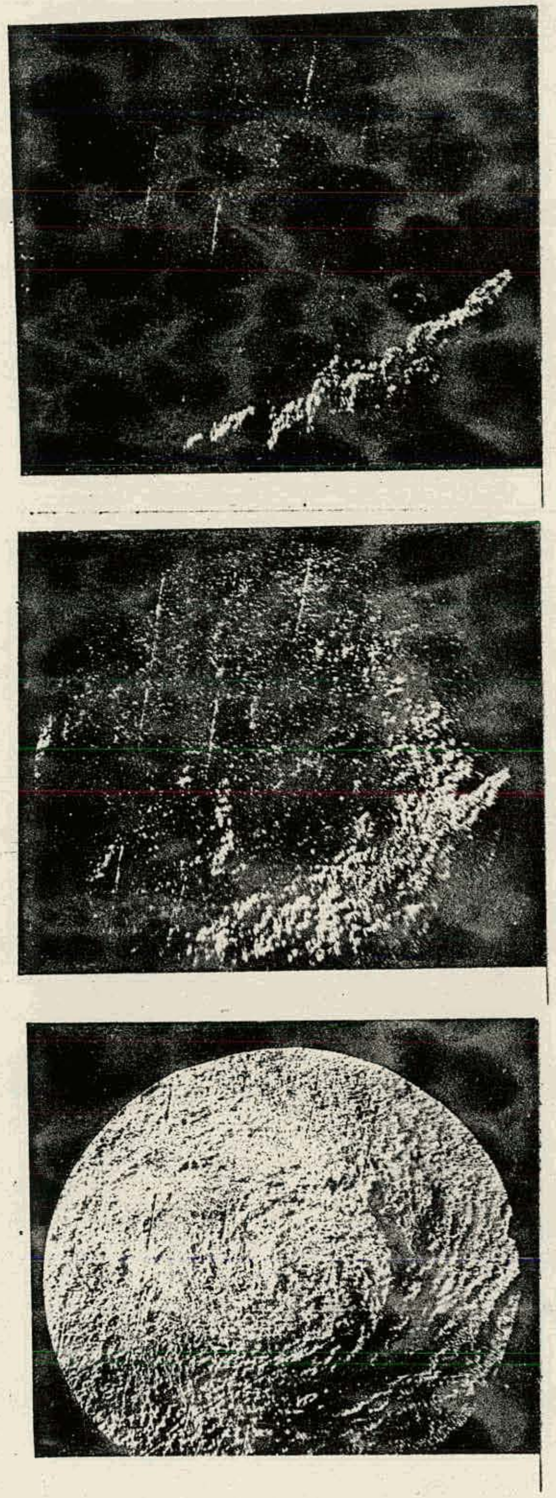


Figure 3. Ethylene concentration as a function of time for quenching under laminar and turbulent conditions.

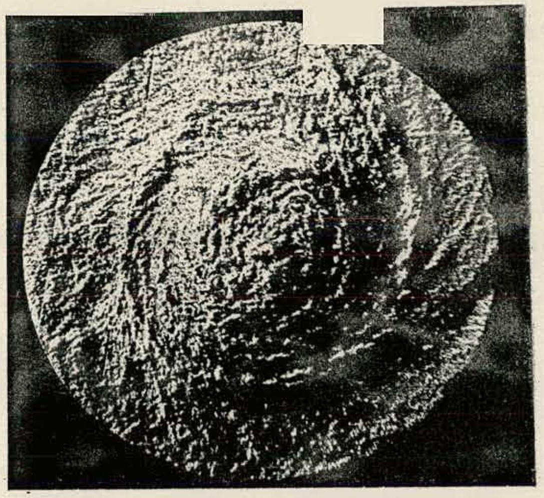


0 milliseconds

36 milliseconds

50 milliseconds

Figure 4 . Schlieren photographs of density gradients in The University of Michigan Combustion Bomb with no ignition, at various time intervals after inlet valve opening.

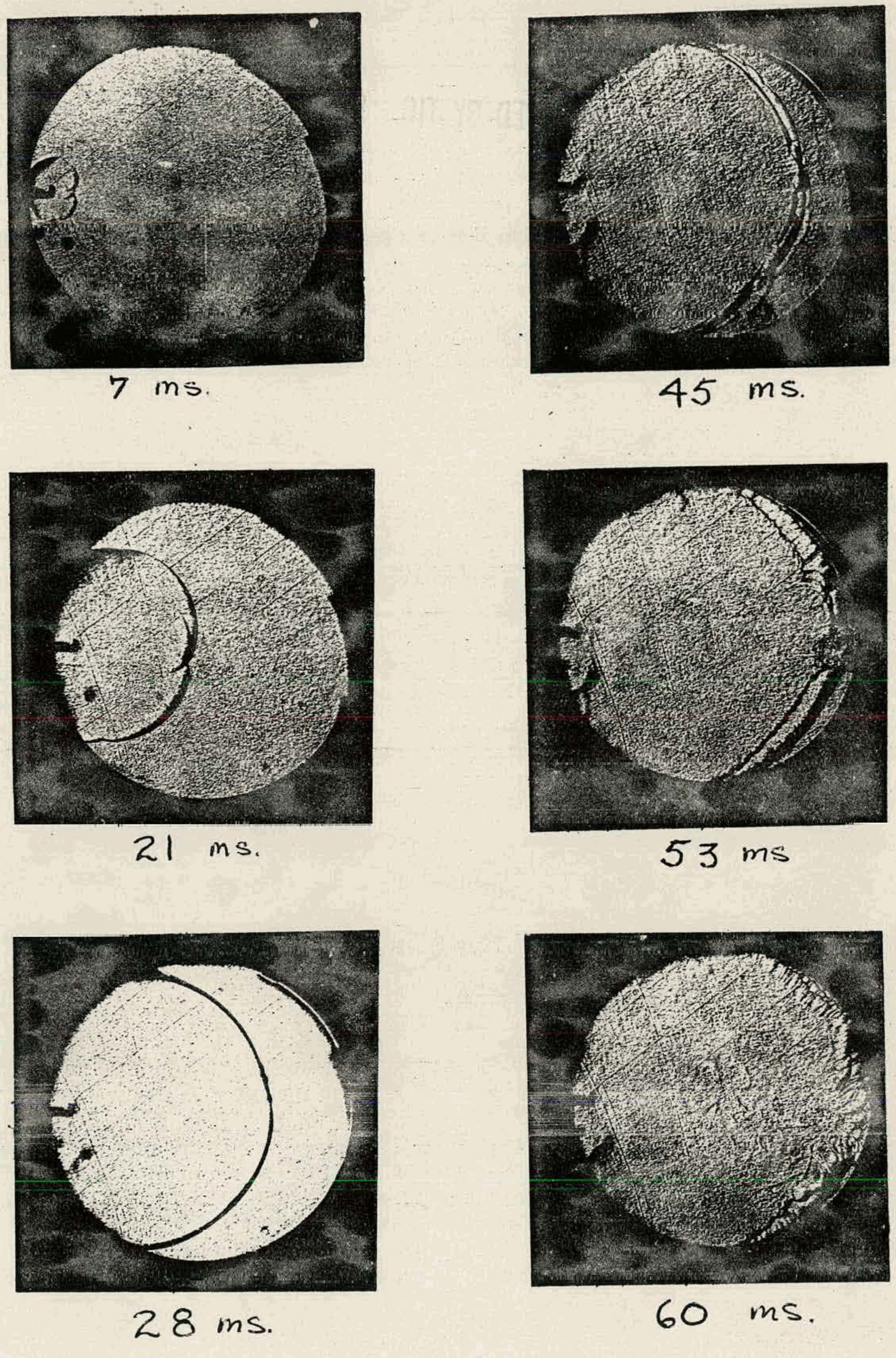


70 milliseconds

180 milliseconds

500 milliseconds

Figure 4. (concluded)



FLAME PROPAGATION THROUGH QUIESCENT PROPANE AIR MIXTURE

Figure 5.