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HC QUENCH LAYER FORMATION
IN COMBUSTION PROCESSES

MASTER

TECHNICAL PROGRESS REPORT
FOR THE PERIOD
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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 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 January to April 1980 and will include a discussion of current technical status, and plans for the final reporting period, May-July 1980.

TECHNICAL STATUS

Significant areas of progress during the reporting period are: (i) the sampling valve data obtained previously in the Ford spherical bomb under quiescent firing conditions have been analyzed and interpreted, (ii) the solenoid-operated charging system has been set up to generate turbulence in the bomb, and the inlet flow has been characterized in terms of pressure, velocity, turbulence, and temperature histories, and (iii) an analysis leading to a simplified model for the turbulent quench layer has been obtained.

A detailed discussion of these items follows:

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

The feasibility of using an electrohydraulic sampling valve on a single shot basis to withdraw quench-layer material has been completed in the Ford spherical combustion bomb. In these experiments, the bomb was filled with premixed propane and air through a low crevice volume inlet and exhaust valve to a pressure of 250 kPa, allowed to sit until the mixture was quiescent (∿ 3 min.), and fired. At preset times after the ignition, small-volume gas samples on the order of 1.5 std cm^3 were then dynamically extracted from the wall region (within ∿ 3mm of the wall) of the combustion bomb. These samples were directly injected into a gas chromatograph and analyzed for CH_4, C_2H_4, C_2H_6, C_3H_6, C_3H_8, CO, CO_2, N_2 and O_2. The Ford spherical combustion bomb was used for this portion of the study, since the Ford cylindrical bomb, which will be used for the remainder of the project, was at the University of Michigan being used to characterize the incoming flow generated by the dynamic charging system -- presented in the section on Task II.

Figure 1 shows a typical reactor pressure trace for the spherical bomb, a fuel molecule (propane) concentration trace and an intermediate species molecule (acetylene) concentration trace, both as a function of time after ignition. Also shown in Figure 1 are the concentrations of these two species which are determined by a bulk gas sample withdrawn from the reaction 5 minutes after firing. These concentrations are indicated by the lines marked "exhaust level" in Figure 1.

As seen in Figure 1, before the flame arrives at approximately 70 ms after ignition, the concentration of the material extracted from near the reactor wall into the sampling valve is identical to the initial composition of premixed fuel, oxidizer and diluent. At the time of flame arrival, the propane concentration drops from its initial value to approximately 1 ppm within 3 ms of the arrival time. After reaching this minimum value, the propane level increases until it reaches an exhaust concentration of 20 ppm.

We interpret the rapid decrease in propane level and subsequent slow rise to the exhaust level as indicative of a two-stage process. The first stage (flame quenching) reduces the propane level to 1 ppm while the second stage (crevice outgassing) raises the propane level to the exhaust value on a time scale of approximately 1 sec.

In these studies, the intermediate species (propylene, acetylene, ethane, ethylene) all peaked at the time of flame arrival. Before flame arrival and within 150 msec after the flame arrival time, these specie concentration levels were below the detectable limits of the gas chromatograph used in the analysis.

To date, all sampling valve measurements have been performed under quiescent initial conditions with a laminar flame propagating through the reactor. The valve has operated as designed with extremely low levels of leakage due to the high sealing forces. Presently, the dynamic charging system is being calibrated and sampling valve measurements of flames quenching under turbulent conditions will follow.

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

As reported in our Technical Progress Report for September-December 1979, we have chosen to generate turbulence in the bomb by introducing the flow into the bomb as a pulsed, high speed jet. The fluid motion and turbulence intensity decays as a function of time after the inlet valve is closed. The combustion bomb is then fired when the turbulence intensity decays to the desired turbulence level. In addition, the turbulence level is further augmented, if desired, by the insertion of a turbulence grid.

The experimental setup shown in Fig. 2 consists of the cylindrical combustion bomb designed at Ford (8.255 cm inside diameter), a directional swirl producing nozzle through which the propane-air charge is injected, a removable turbulence producing grid, and the gas inlet system. An identical inlet setup is being assembled at Ford, and will provide for uniform test conditions and flow patterns at U. of M. and at Ford. Thus, gas concentration measurements obtained at Ford can be correlated with velocity and turbulence measurements made at the The University of Michigan.

The gas inlet system shown in Figure 2 consists of pressure tanks, a solenoid valve, a check valve, and an intake nozzle. The solenoid valve was chosen to have as large an orifice as possible and the shortest open-close times consistent with rapid commercial availability. The check valve is also commercially available and is employed to protect the solenoid valve and premixed charging tank from the combustion pressure. Design of the nozzle took into account two important factors. First, the nozzle produces the desired swirling flow pattern and is flush mounted, i.e. there are no physical projections into the flow causing local recirculation or other disturbances. Initially, it was planned to consider the "no swirl" case first, but it was decided that the addition of swirl would benefit the analytical modelling study since the wall region could then be modelled as a turbulent boundary layer in which the behavior of the turbulence is fairly well known. The second factor in the nozzle design was the question of whether to use a two-dimensional slot in order to inject the flow in a two-dimensional pattern, or to use a circular nozzle which introduces three-dimensional flow. The circular nozzle was chosen for manufacturing simplicity and also in an attempt to minimize crevice volumes in the bomb which would interfere with HC concentration measurements.

For the tests conducted at The University of Michigan, the Ford bomb has been instrumented with a pressure transducer, a hot film anemometer, a schlieren flow visualization system and a miniature thermocouple probe. The piezoelectric pressure transducer has been used to obtain the pressure time history in the combustion bomb, allowing us to determine the effects of charging pressure and valve opening time on the charging rate. The hot film anemometer (SI 1210-20) is a rugged .015 cm diameter probe used to measure instantaneous velocity, mean velocity and RMS velocity fluctuations at various radial locations. To date, efforts have been concentrated on characterizing only the velocity and turbulence levels prior to combustion.

Run parameters used are: charging pressure in the "constant pressure tank" shown in Fig. 2 is 0.6 MPa (90 psia); initial bomb pressure is 0.1 MPa (14.7 psia). The solenoid valve is opened and then closed by supplying a current pulse of 80 msec from a variable pulse generator. Flow through the 0.8 cm directional nozzle is turbulent since the corresponding Reynolds number of the inlet jet when the valve is first opened is 200,000.

The pressure and velocity data were recorded digitally on a floppy disk which was inserted in a Nicolet digital oscilloscope. The hot film anemometer signal was processed by a linearizer circuit set for the calibration conditions of 1 atmosphere pressure and 290^{o}K. Since the pressure and temperature in the bomb are different in general from the calibration conditions, the raw data must be adjusted to obtain true velocity readings. The hot film correction factor is given by the following relation:

$$u(t) = \frac{\text{constant}}{(T_p - T_g)^2} \frac{T_g}{P} \cdot v(t) \qquad (1)$$

where u(t) is the true velocity, v is voltage output from the hot film linearizer, P is the gas pressure, T_g is gas temperature and T_p is the preset probe temperature. The constant is determined from cold flow calibration, T_p is known for a preset probe operating resistance and p(t) and $T_g(t)$ were measured as discussed below. This equation is derived by setting the Nusselt number for a convectively cooled cylinder proportional to the square root of the Reynolds number. In order to minimize the effect of the correction factor $(T_p - T_g)^2$, we raised the probe temperature T_p to 590 K so that for the observed 23 K variations in Tg, the factor $(T_p - T_g)^2$ varied by only 15% from its cold flow calibration value. The factor T_g varies by only 8% between calibration and run conditions. Therefore, the only major correction to the hot film data is the 1/P factor in the above equation.

The pressures, mean velocities, and temperatures measured in the combustion bomb are shown in Figs. 3, 4, and 5. The velocity profiles in Fig. 4 follow a general trend similar to linear solid rotation profiles; however, the mean velocities near the centerline (r/R = 1) do not approach zero. This can be explained by the fact that the center of flow rotation does not coincide with the geometric centerline, as observed in previous schlieren photographs.

The temperatures in the combustion bomb were obtained with a .005 cm (.002 in.) diameter BLH microminiature chromel-constantan thermocouple probe. The manufacturer's specified time response of the probe is 13 msec. As can be seen in Fig. 5, the gas temperature was observed to increase during the first 150 msec due to compressive heating, followed by heat transfer in the radial direction and to the walls during the next three seconds. The sharp peak noticed in the earliest temperature profile at 50 msec after valve opening is believed to be due to the effects of the inlet jet. The maximum measured variation in gas temperature is seen to be 8.3%, which is considerably less than the 21% theoretical increase predicted for idealized adiabatic compression of air from 1 to 2.4 atm, which is a further indication that the inlet flow process is not adiabatic.

Another quantity of interest is the turbulent velocity fluctuation level, which can be determined from the digitized hot film data. Velocity fluctuation levels corresponding to the data of Figs. 3, 4, and 5 have not yet been deduced, however, typical raw voltage data for slightly different run conditions are shown in Fig. 6. In order to obtain the RMS voltage fluctuations, each hot film voltage time history was fit with a mean voltage curve, and the voltage fluctuations from this mean voltage curve were then squared and summed. The root-mean-squared (RMS) voltage fluctuation is the square root of this number. When additional future data becomes available, the voltage time history will be divided into discrete regions so that a time history of the RMS fluctuating level can be deduced.

Methods are now being studied to correct the hot wire data for pressure and temperature effects on the RMS velocity fluctuations. From Eq. (1) it can be shown that:

$$\frac{\overline{u'^2}}{\bar{u}^2} \doteq \frac{\overline{V'^2}}{\bar{v}^2} - \frac{\overline{p'^2}}{\bar{p}^2} + \frac{\overline{T_g{}'^2}}{\overline{T_g}^2} \qquad (2)$$

Additional correlation terms also can appear in Eq. (2). However, since the physical mechanisms driving the velocity, temperature and pressure gradients are different, it can be assumed that such correlations are negligible, as is routinely done in supersonic flows. Furthermore, it is believed that the last term in Eq. (2) is negligible since it is proportional to the square of the mean temperature gradient, which is much smaller than velocity or pressure gradients. Methods to uncouple the velocity and pressure effects on the hot wire are now being studied.

Finally, the effects of inserting a turbulence-producing grid into the bomb were studied. As seen in Fig. 7, the grid apparently converts the directed flow velocity into turbulent kinetic energy, causing a four-fold decrease in mean flow velocity and a four-fold increase in the voltage fluctuation levels $V'_{RMS}/\overline{V}$. However, since the turbulence thus produced is somewhat periodic, with fluctuation peaks occurring once every flow revolution, it was decided to discontinue the use of the grid.

Task III Analytical Study (University of Michigan)

The analysis leading to a simplified model for the turbulent quench layer has been completed. In this model, no detailed reaction mechanisms are employed; rather, it is assumed that as the flame passes over the wall, there is a region of combustible mixture which does not react because the heat transfer at the wall has reduced the temperature below the ignition temperature. A schematic of the flow geometry is shown in Figure 8. The case where swirl exists in the combustion chamber is considered, such that a fully developed turbulent boundary layer exists along the wall. The thickness of the boundary layer is assumed to be small compared to the radius of the cylinder, so that the pressure gradient across the boundary layer is negligible. In addition, the Mach number of the core flow is small enough that the pressure gradient in the direction of flow is negligible; this is essentially equivalent to assuming solid body rotation in the cylinder, with a characteristic time for decay large compared with the time characteristics of the reactions. Thus, to lowest order, the flow in the boundary layer is described by solutions valid for flow over a flat plate.

Although the flow velocity at the edge of the boundary layer is small compared to the speed of sound, the temperature variation is enough that the variation in density is important. The laminar and turbulent Prandtl numbers are taken to be unity and the temperature of the wall is constant. Hence, since the pressure gradient is negligible, the Crocco integral is a solution of the energy equation which gives the temperature distribution in terms of velocity distribution.

The velocity distribution for the compressible, low Mach number, boundary layer is found in terms of a corresponding incompressible boundary layer velocity profile. An asymptotic analysis is used to find relationships between the corresponding parameters in the incompressible and compressible flows. Thus, an equation is found which gives the dimensionless friction velocity in terms of the dimensionless boundary layer thickness and the Reynolds number associated with the core flow at the edge of the boundary layer. A momentum integral equation provides another relationship between these three quantities. Finally, again from the asymptotic analysis, one can find an equation for $\tilde{\delta}$ in terms of δ and the Reynolds number, where $\tilde{\delta}$ is the dimensionless thickness of the wall layer part of the boundary layer in the same sense that δ is the dimensionless thickness of the boundary layer. The result is that for a given Reynolds number and temperature ratio across the boundary layer, one can calculate δ and $\tilde{\delta}$. Now, it can be shown that y+, the variable which correlates the velocity in the law of the wall region of the turbulent boundary layer, is

$$y+ = y/\tilde{\delta}$$

where y is the dimensionless physical distance from the wall. Thus, it is clear that for any given $y+$, the corresponding physical distance, y, can be calculated once δ is known.

The thickness of the quench layer, i.e., the distance from the wall to the point at which the given mixture can be ignited, is calculated as follows:

(1) For a given swirl velocity, mixture of combustion products, and temperature, the Reynolds number is calculated.

(2) For prescribed wall and combustion temperature, and the Reynolds number calculated in step (1), $\tilde{\delta}$ is calculated.

(3) The ignition temperature corresponding to the given reactant mixture is used in the Crocco integral to calculate the corresponding velocity at the ignition point, u_{ig}, and the corresponding incompressible velocity is then calculated.

(4) Using equations which correlate experimental data in the wall layer region, the value of $y+$ at u_{ig}, say y^+_{ig}, is calculated, and finally $y_{ig} = \tilde{\delta}\, y^+_{ig}$ is found. This, then, is the estimate of the thickness of the quench layer.

Typical values for the thickness of the quench layer, calculated for various hydrocarbon fuels, both rich and lean mixtures, range from 0.005 cm to 0.01 cm. Presently, experimental results are being sought for comparison and a computer program for the calculation of y_{ig} is being written. The computer program will allow a rapid investigation of the variation of y_{ig} with the various parameters involved.

Plans for the Next Period (May-July, 1980)

The cylindrical combustion bomb will be assembled at Ford with the dynamic charging system incorporated in the apparatus. The time interval between induction of the charge into the bomb and ignition will be varied to alter the degree of fluid motion in the bomb at the time of flame quench. The Ford sampling valve will be mounted in this reactor and gas samples will be extracted from the wall layer as a function of time after flame arrival and mass inducted into the valve. These data will be used in conjunction with the velocity measurements obtained at the U. of M. to determine the relationship between turbulence and the amount of hydrocarbons remaining in the reactor after firing.

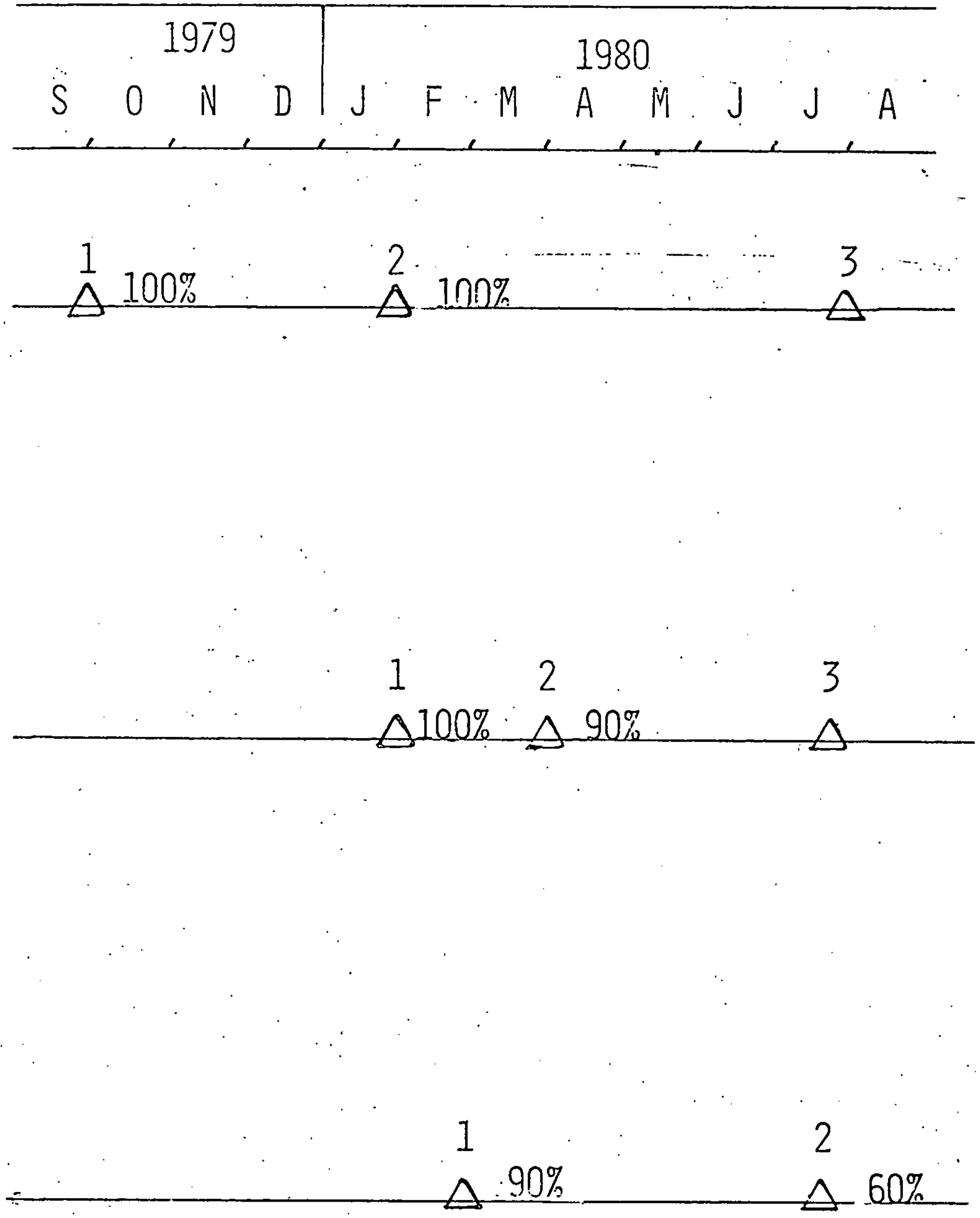
At U. of M. work will continue on reduction of hot film data to obtain velocity fluctuation information from the voltage traces. Specifically, methods to uncouple velocity and pressure effects on the results will be investigated. Also, laser velocimeter measurements of local flow velocity will begin and several possible experimental problem areas will be studied. It is expected that velocity data will be obtained, but it is anticipated that extensive work will be required to obtain sufficient data rates so that meaningful statistical averages can be computed.

During the next period, preparations will be made to operate the bomb in the combustion mode, requiring various safety considerations to be implemented.

In the analytic studies, the comparison of calculated and experimental values of y_{ig} will be continued. It is planned that the computer program for the rapid calculation of y_{ig} will be completed.

One of the points of contention in using the concept of a quench layer, is the amount of fuel which diffuses out of the layer and then reacts during the expansion stroke of an I.C. engine. An effort to make a relatively careful estimation of this mass loss has begun and will be continued. In this regard, both laminar and turbulent transport must be considered and it appears that thermal diffusion may be important as well. Also, because in the actual engine, the process is unsteady, an analysis will be made to show whether or not the process may be considered to be quasi-static.

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

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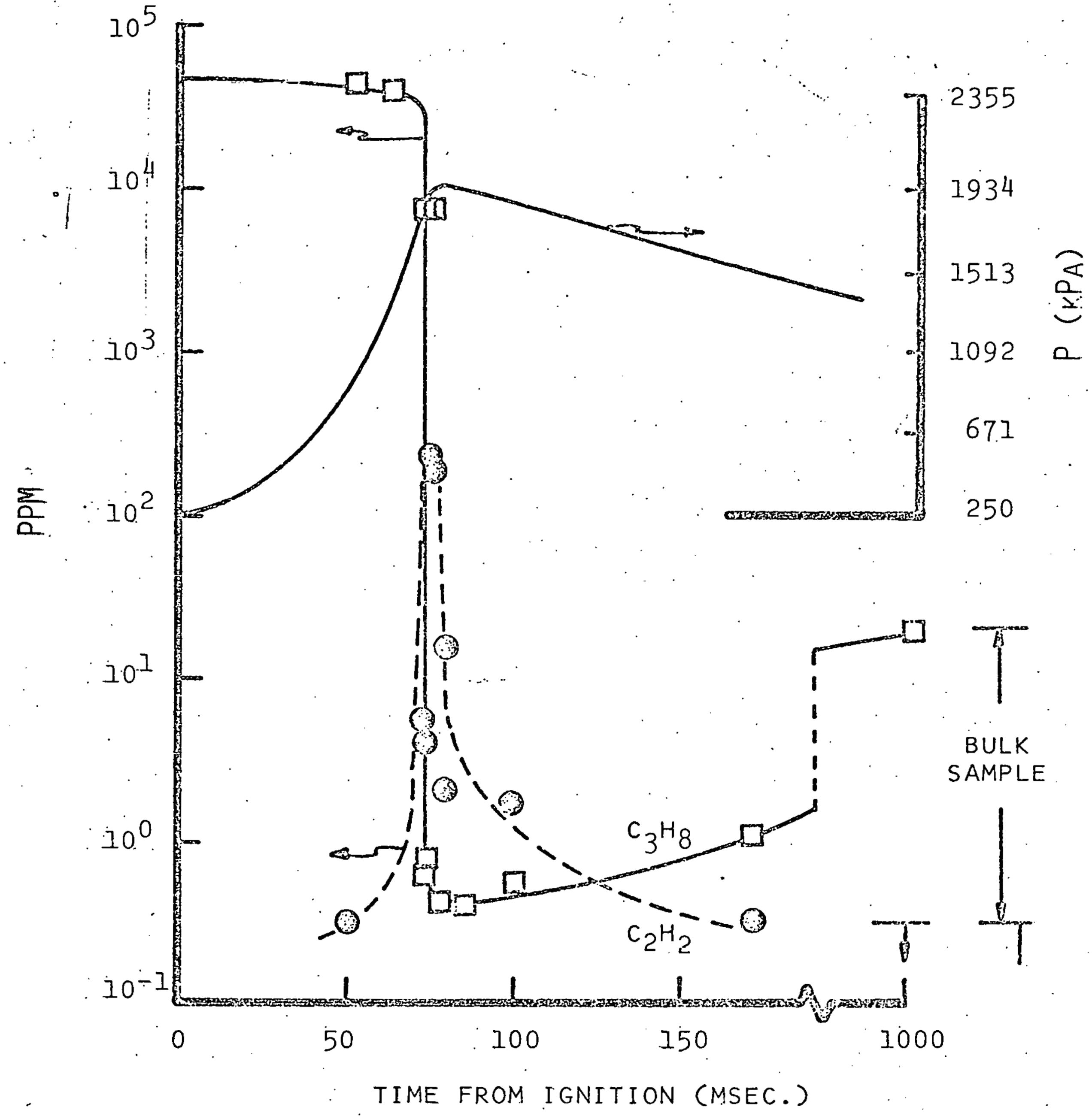


FIGURE 1. WALL LAYER HYDROCARBONS OBTAINED WITH SAMPLING VALVE FOR LAMINAR COMBUSTION CONDITIONS. UPPER PART OF FIGURE SHOWS CORRESPONDING PRESSURE TRACE. HORIZONTAL LINE AT RIGHT DENOTES AVERAGE BULK GAS SAMPLE.

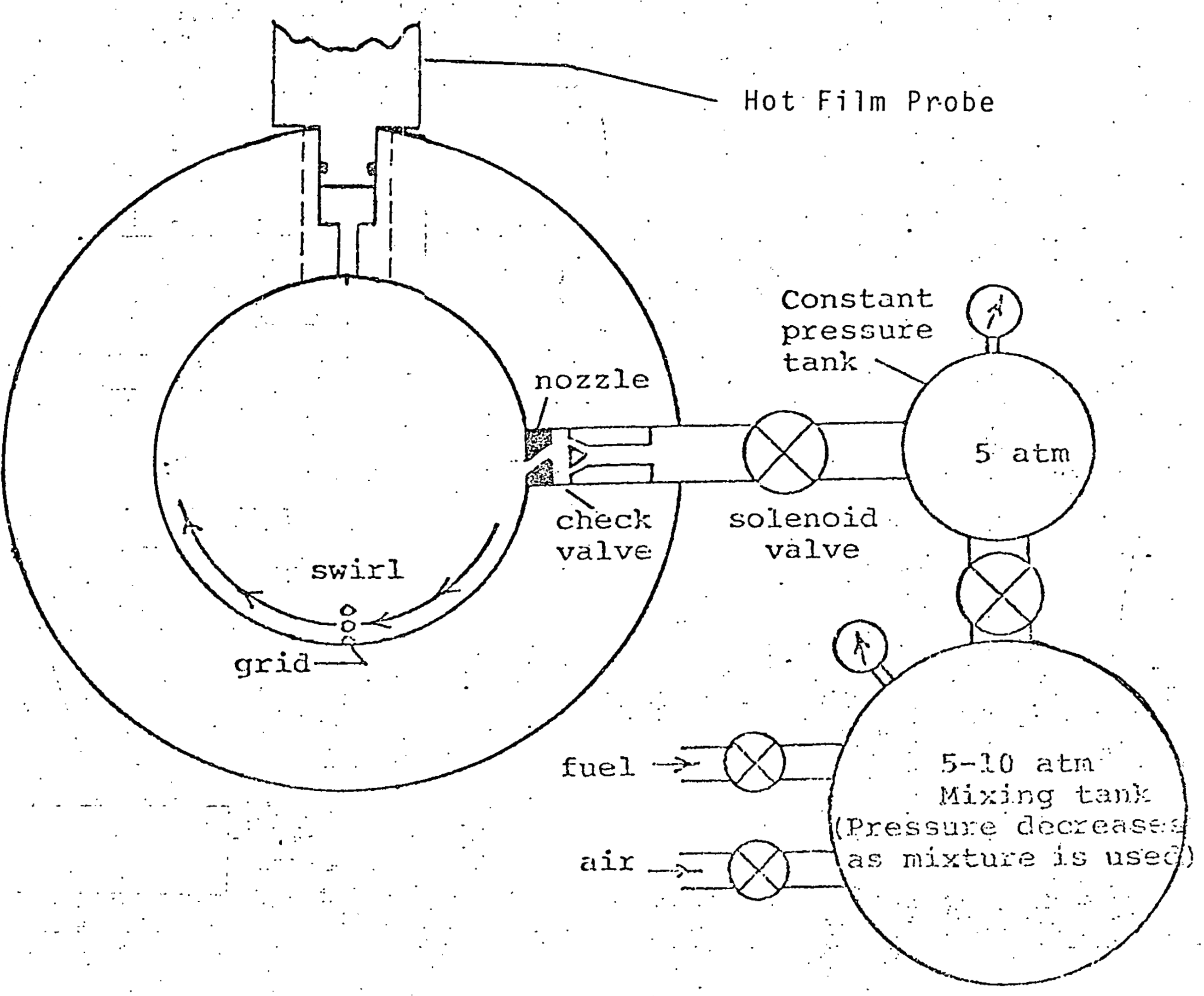


Fig. 2. View through windows (along axis) of cylindrical combustion bomb

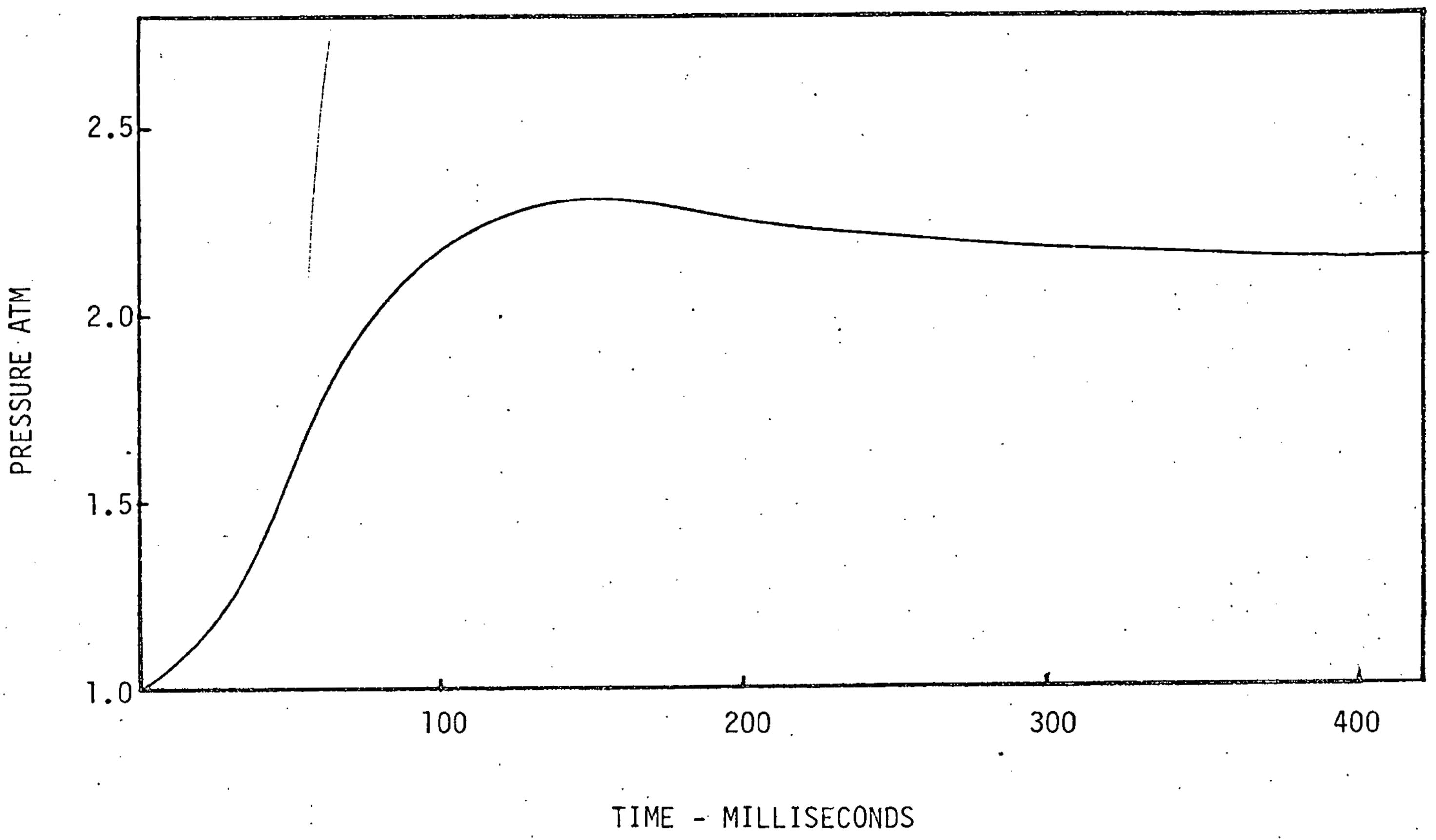


Figure 3. Pressure time history in the combustion bomb
Driving pressure 6 atm; Solenoid pulse 80 msec

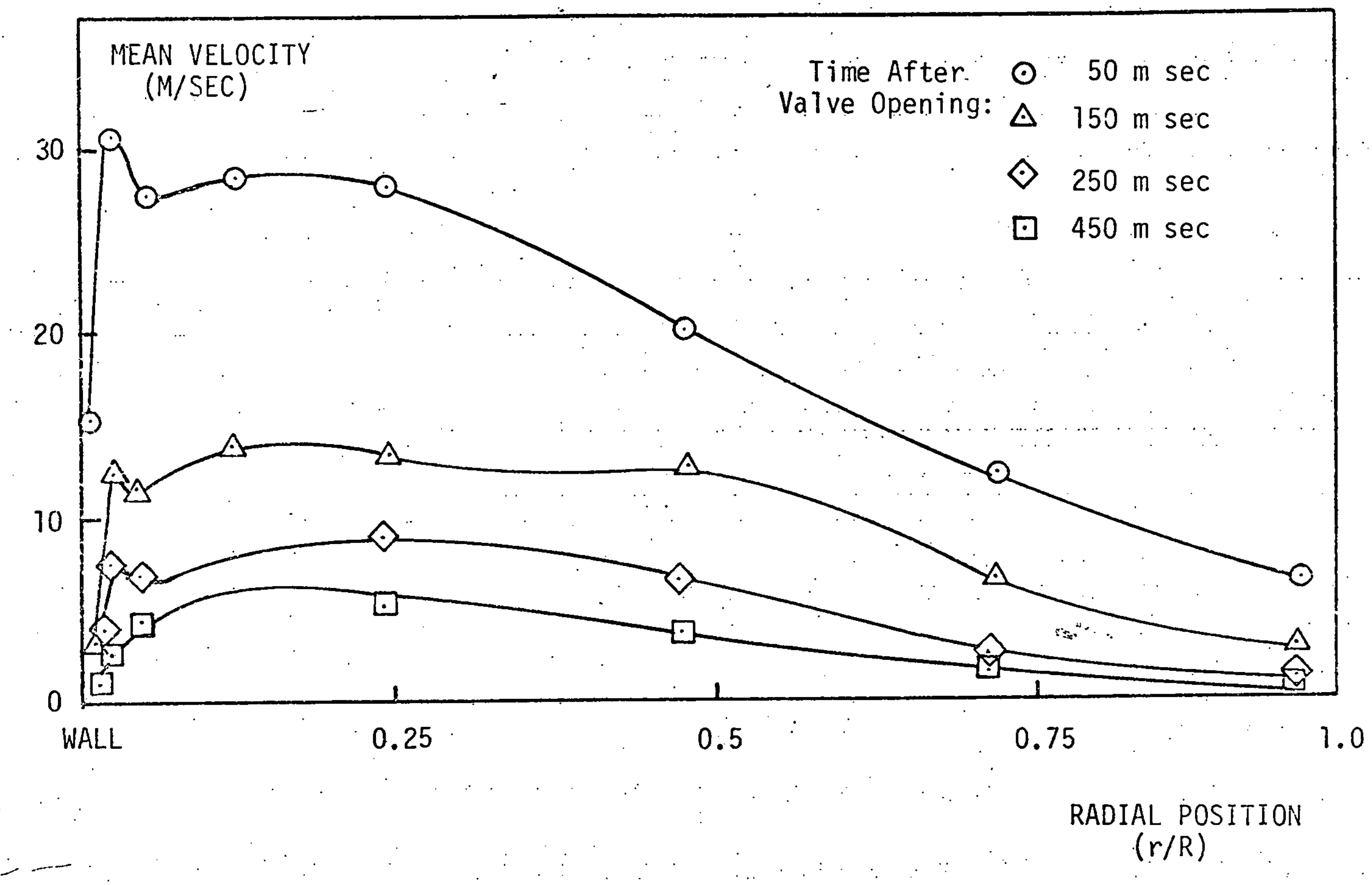


Figure 4. Mean Velocities in Ford Combustion Bomb
Bomb Radius R = 41.275 mm

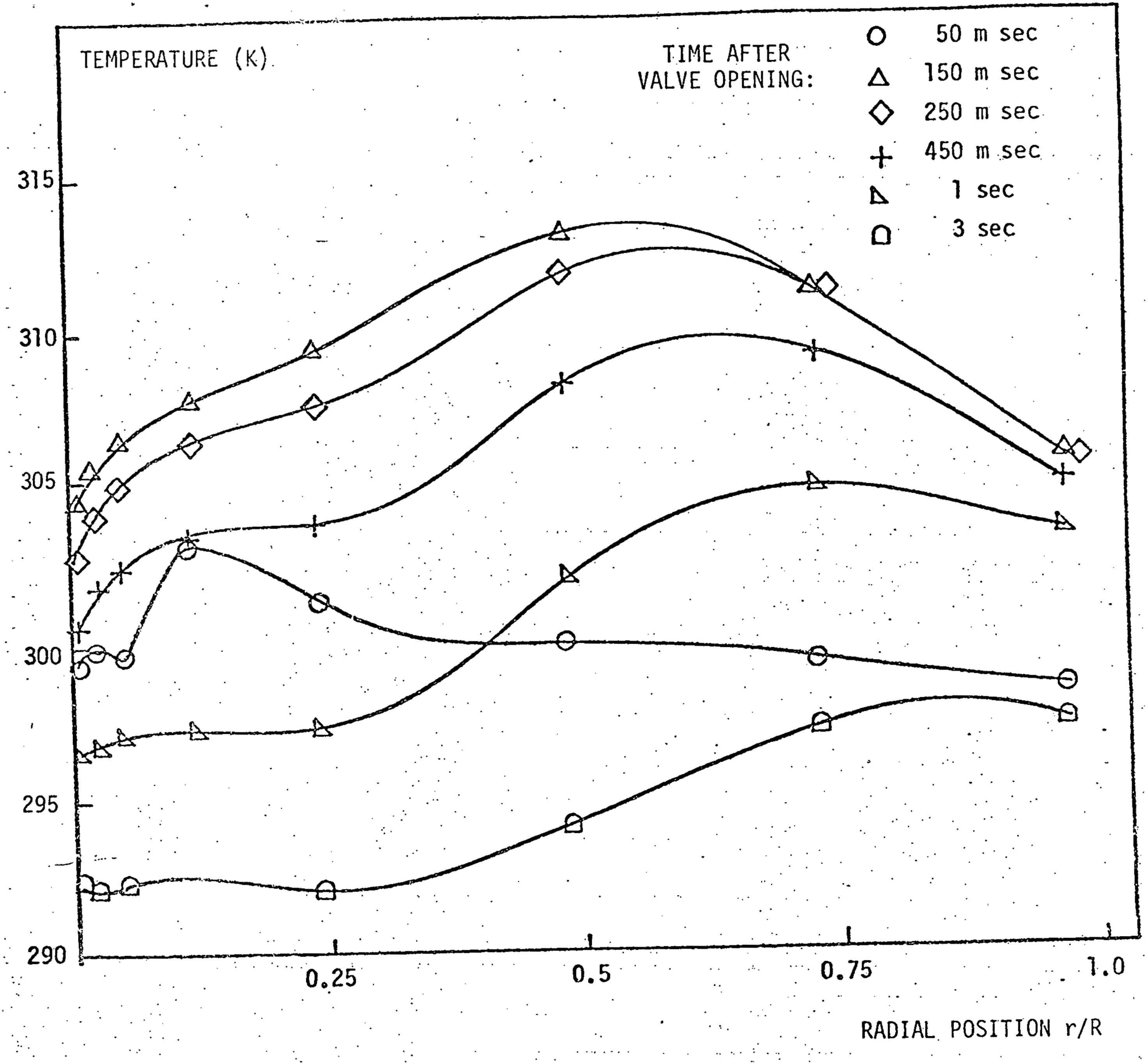


Figure 5. Gas Temperature Measured in Ford Combustion Bomb Bomb Radius R = 41.2 mm. Note that inlet valve current pulse remains on until 80 msec.

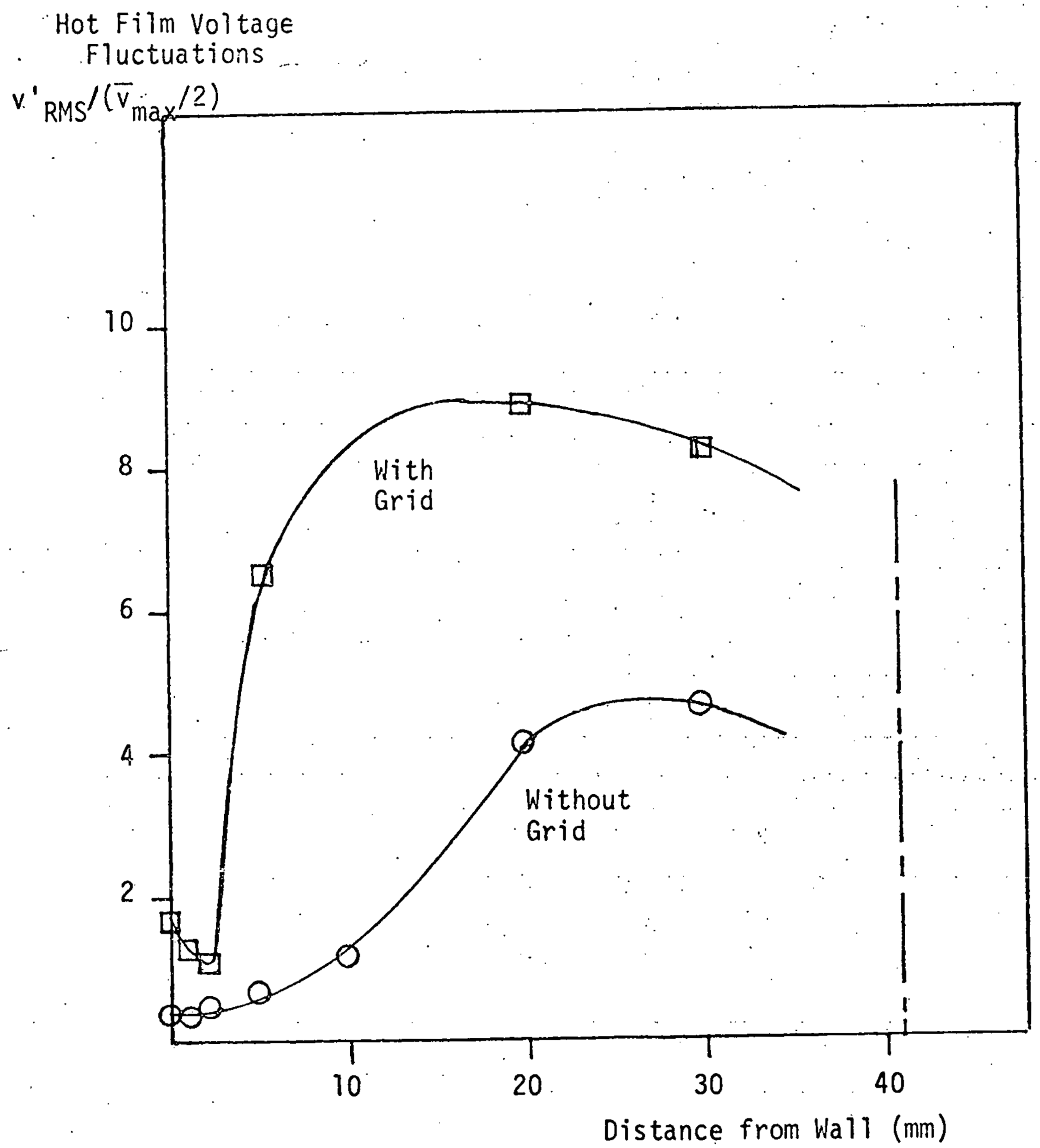
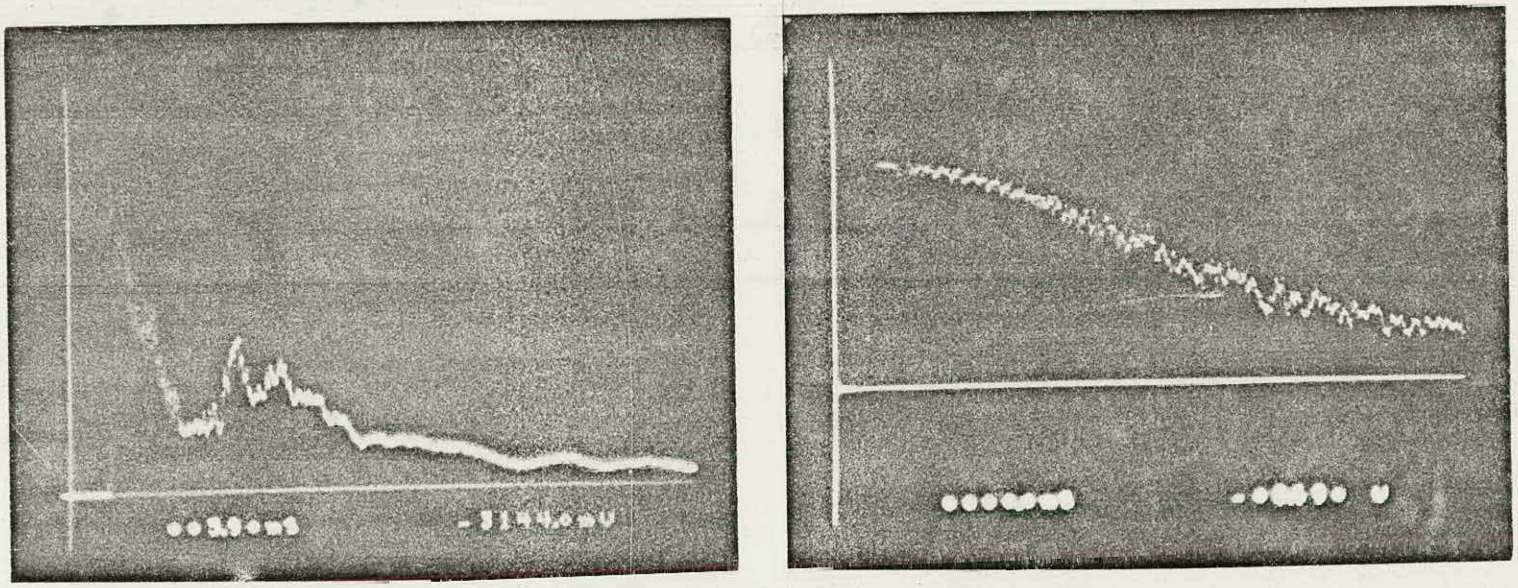


Figure 6. Turbulence Intensity in Combustion Bomb



Velocities Measured with
Turbulence Grid

z = .1 cm from wall
x axis = 409 m sec full scale
peak velocity 9.2 m/sec
driving pressure 80 psig

Velocities Measured with
No Grid

z = .1 cm from wall
x axis = 1023 m sec full scale
peak velocity 42 m/sec
driving pressure 80 psig

Grid causes a decrease in mean velocity
Grid causes velocities to decay faster
Grid causes repeatable velocity peaks

Figure 7. Effect of Turbulence Grid

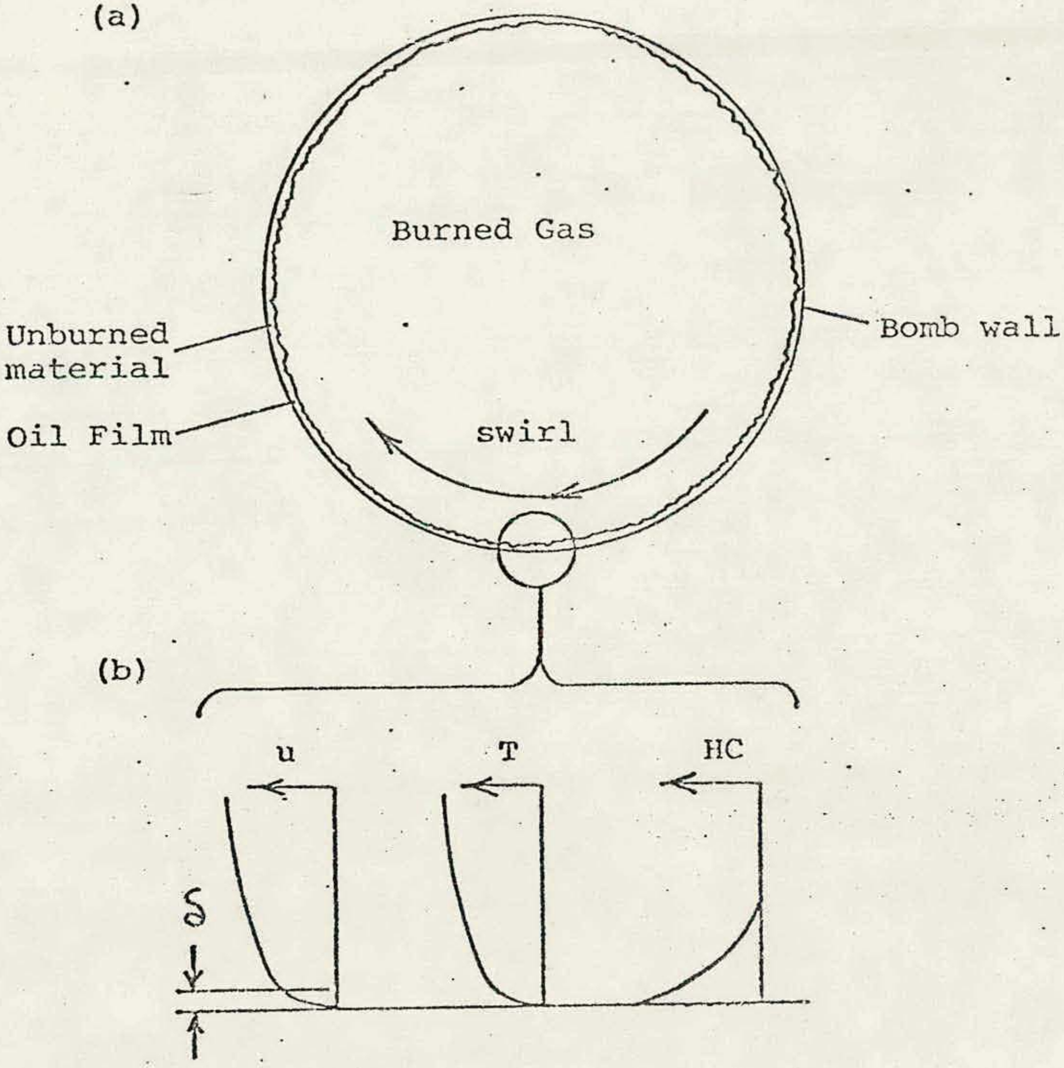


Figure 8. Schematic of wall quenching model

(a) General arrangement showing swirling, burned gas and residual material on wall

(b) Idealized picture of flow-wall interaction showing profiles of velocity, temperature and unburned material.