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A PARAMETRIC STUDY OF QUENCH LAYER HYDROCARBONS USING A FAST SAMPLING VALVE

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INTRODUCTION

An important problem in the control of environmental pollution is the elimination of unburned hydrocarbons from the exhaust of spark ignition engines. The cool quench layers on the combustion chamber walls are a major source of such hydrocarbons. A better understanding of the formation and behavior of these quench layers is necessary for the design and evaluation of systems for reducing unburned hydrocarbons in automobile exhausts.

To study this problem a fast acting valve was used to sample the gas close to the wall of a standard C.F.R. engine. The investigation was concerned with revealing the effects of engine operating conditions on the mass of carbon per unit area on the wall, M_c/A, and the quench layer thickness, δ_q. The M_c/A was found to be invariant and in close agreement with estimated values (1). The quench layer thicknesses during exhaust, δ_q, were approximately .04 cm and are consistent with figures published by Daniel and Wentworth (2).

EXPERIMENTAL FACILITY

The study was performed on a C.F.R. engine. Samples were taken over the entire cycle for the operating conditions in Table 1. Sampling was accomplished using a magnetically driven needle valve with a 2 mm orfice. The sample valve was located in the clearance volume flush with the cylinder wall and diametrically opposite the spark plug.

Figure 1 shows the continuous sampling system used. Sampled gas was delivered to a Scott 215 total heated hydrocarbon analyzer through a heated stainless steel line. Sample flow rates and leak rates were measured using water displacement meters. The flow meters were sized for speed and accuracy

of measurement. For this reason the leak rate meter diameter was much smaller than the flow rate meter diameter. An electronic system capable of phasing sample time and crank angle was used. A rotary generator supplied a voltage pulse every 10° of rotation. These pulses provided crank angle markers, oscilloscope sweep trigger, and crank angle phasing for digitized pressure data. Sampling was controlled by the oscilloscope delay trigger.

EXPERIMENTAL RESULTS AND ANALYSIS

The data taking procedure consisted of measuring a leak rate; measuring a sample flow rate and sample hydrocarbon concentration; initiating computer pressure data acquisition; and finally, measuring a leak rate.

Figure 2 shows a typical oscillograph. Pressure trace, crank angle markers, valve lift profile, and spark timing were displayed. Cycle to cycle variations in valve lift profile were minimal.

The time resolved sample hydrocarbon concentrations are shown in Figure 3. The bar through each data point represents the sample duration. Total hydrocarbons were measured in parts per million of carbon, ppmC.

The sample valve leak rate of 1% accounted for roughly 60% of the measured hydrocarbons during expansion and 15% during exhaust. This condition made hydrocarbon concentration corrections necessary. A close look at the behavior of the leakage revealed that leak rate was strongly pressure dependent. In accordance with these findings a leakage model based on viscous flow through fine capillaries was developed. The ratio of hydrocarbons leaked to the leak rate, $\dot{V}_{CL}/\dot{V}_{L}$, was calculated as follows:

$$\frac{\dot{V}_{CL}}{\dot{V}_L} = \frac{\int_{IVC}^{\text{Flame arrival at sample valve}} (P - P_a)\, d\theta}{\int_{IVC}^{EVO} (P - P_a)\, d\theta}$$

$\dot{V}_{CL}/\dot{V}_L$ = .29 for the operating conditions tested. Hydrocarbon concentrations were corrected by

$$\frac{N_C}{N} = \frac{\delta V_o\, N_{CS}/N - .29\, \dot{V}_L\, \delta t\, N_{CL}/N}{\delta V_o}$$

where

N_C/N ∿ corrected hydrocarbon concentration

N_{CS}/N ∿ sample hydrocarbon concentration

N_{CL}/N ∿ leakage hydrocarbon concentration

δV_o ∿ volume sampled/cycle

δt ∿ cycle time

As a first approximation the flow into the sample valve was modeled as radial and inviscid. Sampled gases were assumed to occupy hemispherical regions concentric with the sample valve orifice as shown in Figure 4a. Sample volumes at ambient conditions, δV_o, were computed by

$$\delta V_o = \frac{Q}{RPM/2}$$

where Q ∿ sample flow rate. These volumes were transformed to in-cylinder volumes, δV_{cyl}, by requiring mass conservation. Therefore

$$\frac{\delta V_{CYL}}{\delta V_o} = \frac{\rho_o}{\rho_{CYL}} = \frac{\rho_o}{\rho_i}\,\frac{V_{CYL}}{V_i}$$

where

V_{CYL}/V_i ∿ cylinder volume/inlet volume

ρ ∿ density

Isentropic expansion to exhaust conditions was assumed when computing δV_{CYL} for samples taken during blowdown and exhaust. Once δV_{CYL} is known the sample hemisphere base area, A, is known and

$$\frac{M_C}{A} = \frac{P_o}{\bar{R}\,T_o} \frac{M_{WC}}{A} \frac{N_C}{N} \delta V_o$$

where

M_{WC} ∿ molecular weight of carbon

P_o, T_o ∿ pressure and temperature, respectively, at ambient conditions

$\bar{R}$ ∿ universal gas constant

The quench layer thicknesses during exhaust were calculated by dividing the M_C/A by the density of hydrocarbon in the inlet charge evaluated at wall temperature and atmospheric pressure.

DISUCSSION OF RESULTS

During the intake stroke the hydrocarbon concentrations shown in Figure 3 increase smoothly from the hydrocarbon concentration of the residuals to approximately 10^5 ppmC. After flame quenching, concentrations drop from relatively constant values during compression to less than 10^3 ppmC. During expansion thickening quench layers occupy greater portions of the sample volumes which results in increasing hydrocarbon concentrations. Exhaust is characterized by relatively constant concentration.

The expected step increase late in exhaust owing to a hydrocarbon rich

roll up vortex was not observed. Schlieren flow visualization of quench layer hydrocarbons (3) indicate that the roll up vortex has moved off the cylinder wall and out of sampling range.

The M_c/A is plotted against crank angle in Figure 5. An average value for the three operating conditions of $.85 \times 10^{-6}$ g/cm^2 is observed during exhaust. This compares reasonably well with an estimate of 2.2×10^{-6} g/cm^2 made using correlations for quench layer thickness (5,6).

The most striking feature of the M_c/A plot is the unrealistic fall off during expansion. One reason for this is the inadequecy of the inviscid model during expansion. Figure 4b illustrates that the inviscid approximation is a good one during exhaust because the velocity boundary layer and quench layer are approximately the same thickness. However, during expansion the quench layer is thinner than the velocity boundary layer and viscous effects become important. A preliminary check indicated that the viscous correction (4) during expansion is not sufficient to bring these values up to the average. This suggests that another effect is present. A likely candidate is the effect of hydrocarbon concentration correction. Expansion samples are much more sensitive to corrections for leakage since over half the measured concentration is leaked hydrocarbons. This is not the case for exhaust samples which have measured concentrations a factor of ten greater than expansion samples.

Quench layer thicknesses were computed for exhaust and found to have an average value of..037 cm for the three operating conditions. Thicknesses were approximately constant for all crank angles.

CONCLUSIONS

A C.F.R. engine and continuous fast sampling system were used to investigate the effects of engine operating conditions on the quench layer hydrocarbons. Based on the findings in this study the following conclusions are drawn:

1) The continuous flow sampling system proved effective for acquiring data rapidly over a range of engine operating conditions.
2) The average M_c/A was the same for the three operating conditions studied and compared favorably with estimates.
3) The average exhaust hydrocarbon emissions of 2000 ppmC corresponds to quench layer swept from half the cylinder wall area.
4) Sampling during intake suggested thorough mixing of residuals and incoming charge.
5) The failure to observe the hydrocarbon rich vortex is due to the fact that it was too far from the wall to be within the range of the volume sampled.
6) To improve the accuracy of the results during the expansion stroke it will be necessary to reduce valve leakage substantially below 1% and apply corrections for viscous flow. Both these tasks are currently being undertaken.

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Table 1 : Operating Conditions

	Lean	Reference Condition	Throttled
Fuel		Isooctane	
Compression Ratio		7.24	
RPM		1000	
θ_{SP}(°ATC)		-25	
P_{inlet}(atm)		1	.72
T_{inlet}(°C)		80	
ϕ	.90	1.0	

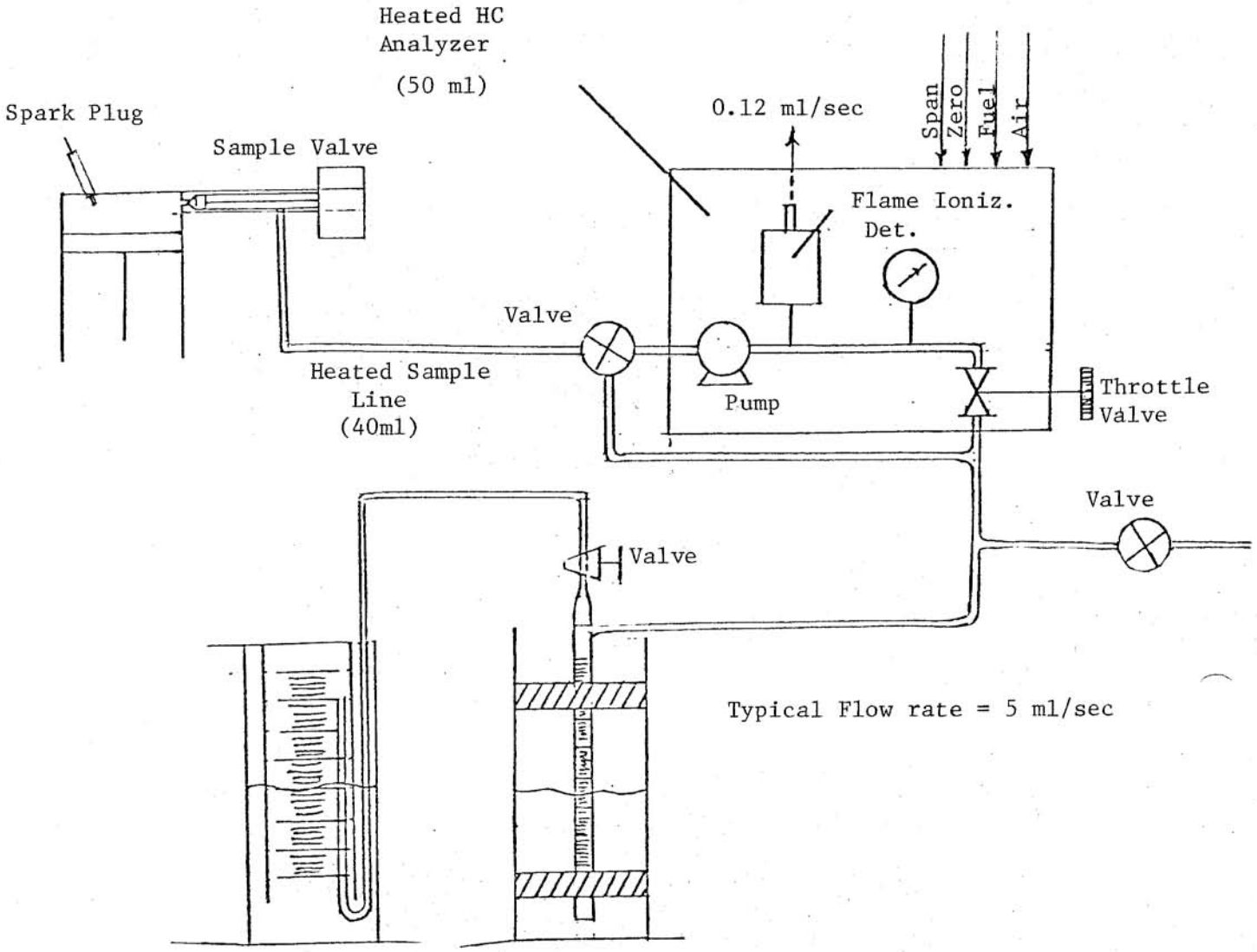


Figure 1: Sampling System

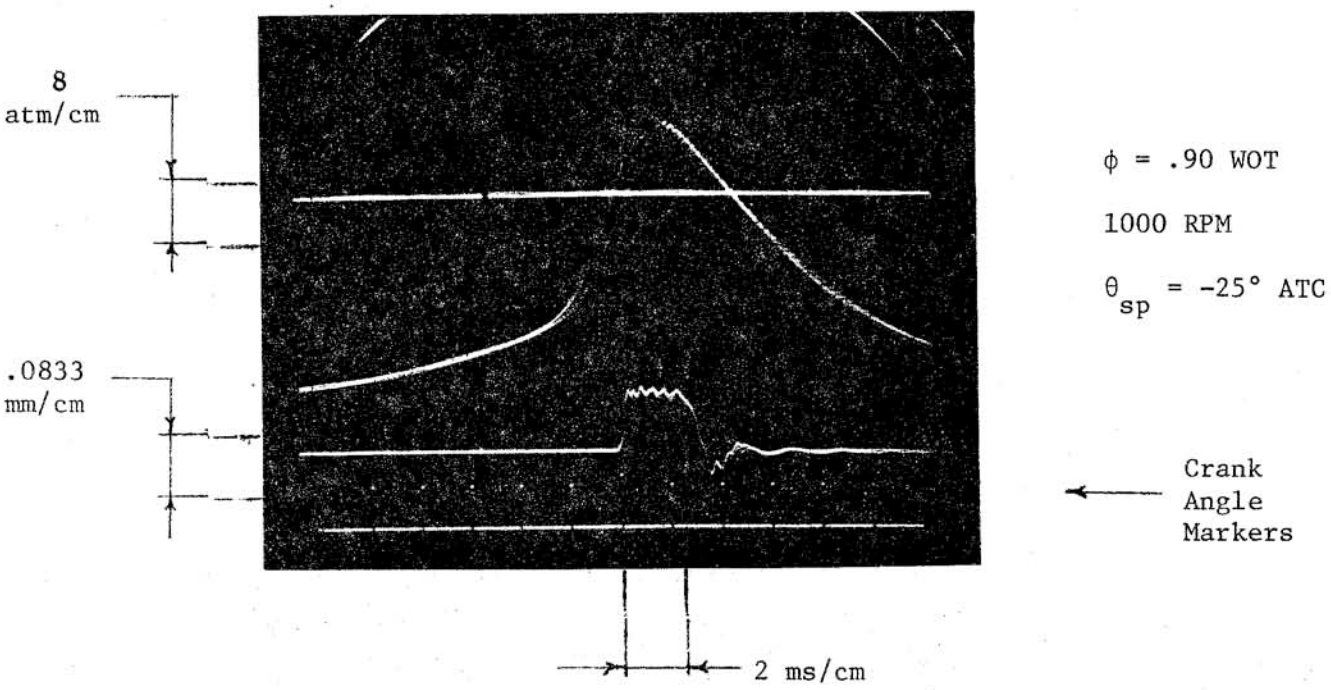


Figure 2. Typical Oscillograph

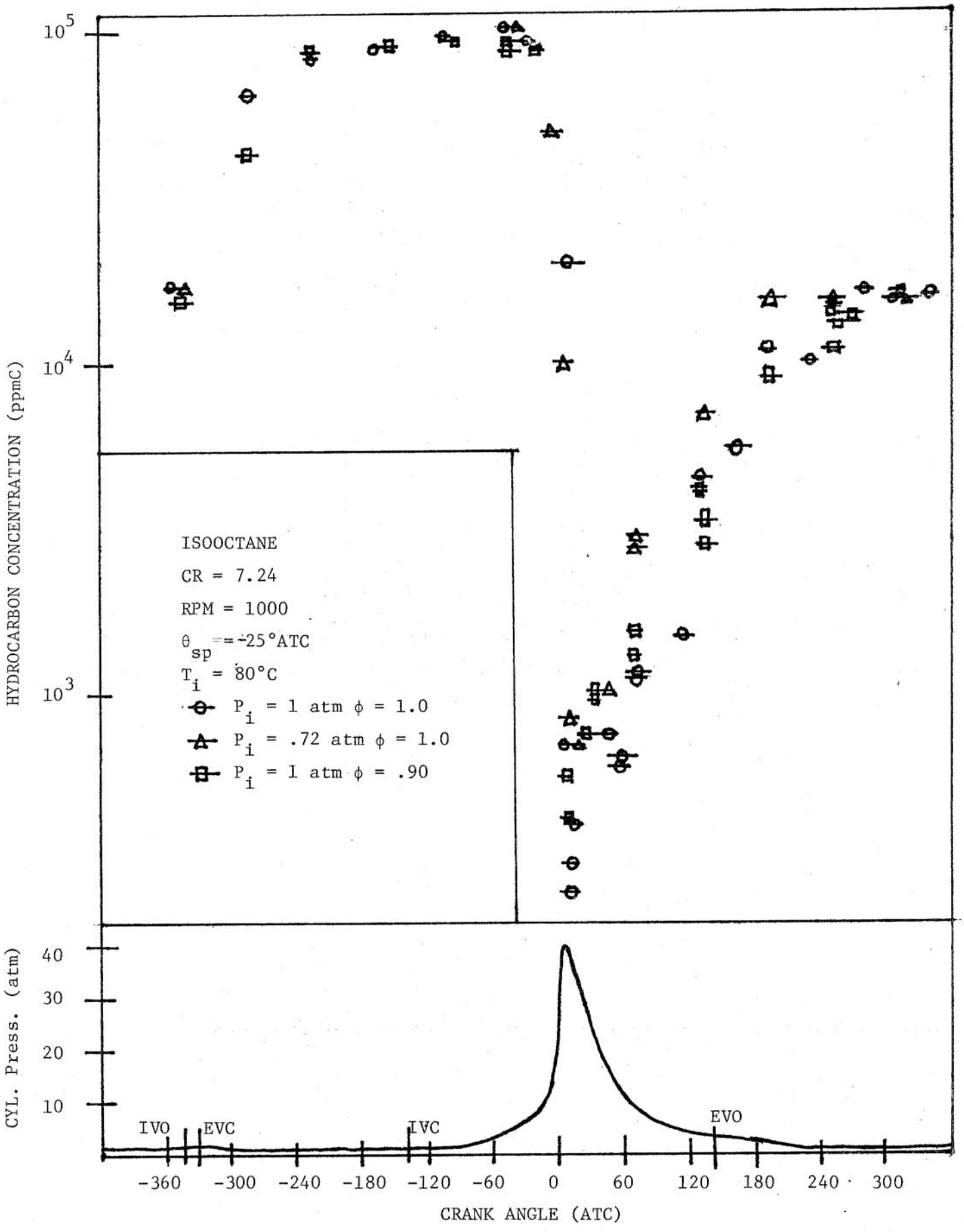
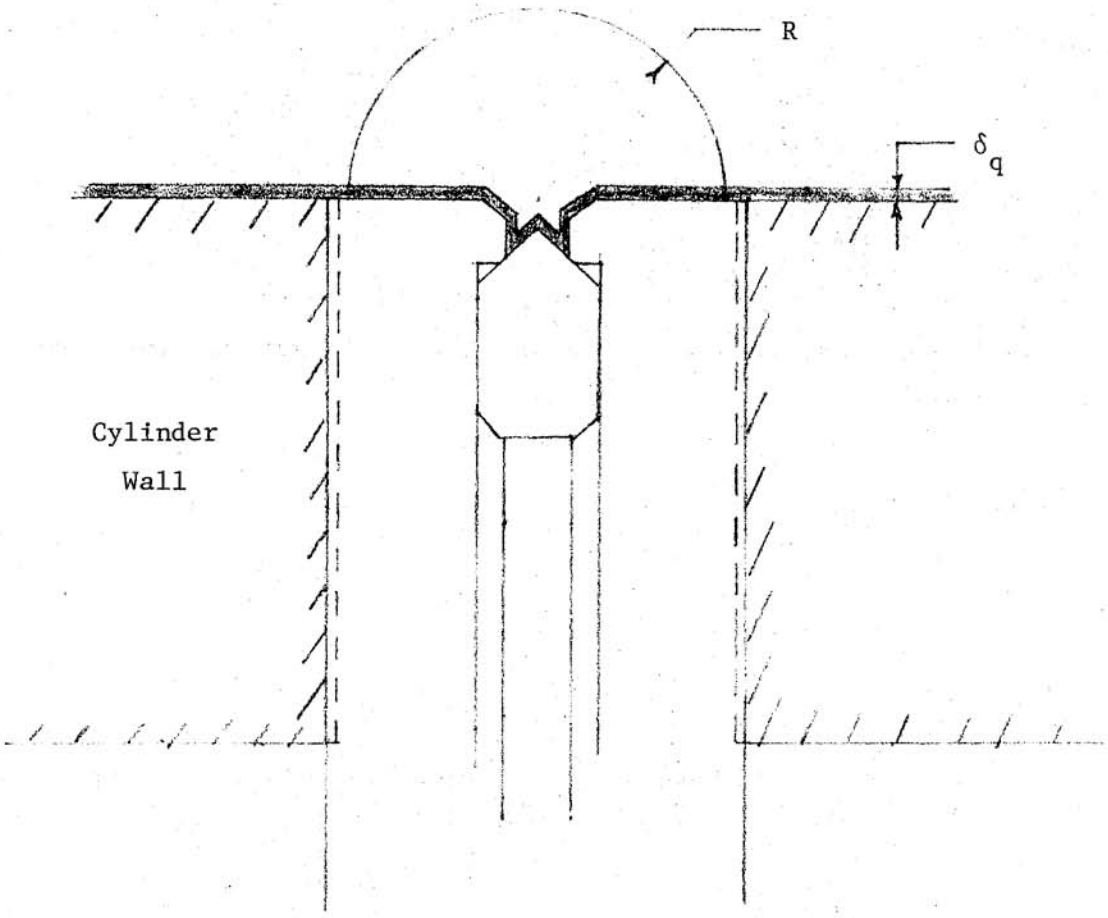
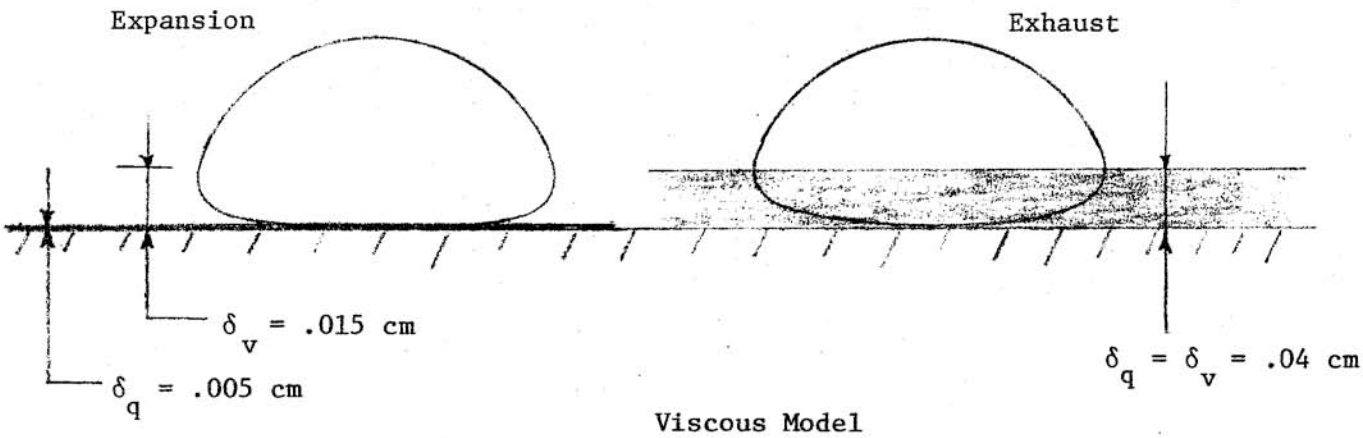

HYDROCARBON CONCENTRATION (ppmC)
10^5
10^4
10^3
ISOOCTANE
CR = 7.24
RPM = 1000
θ_{sp} = -25°ATC
T_i = 80°C
P_i = 1 atm ϕ = 1.0
P_i = .72 atm ϕ = 1.0
P_i = 1 atm ϕ = .90
CYL. Press. (atm)
40
30
20
10
IVO
EVC
IVC
EVO
-360
-300
-240
-180
-120
-60
0
60
120
180
240
300
CRANK ANGLE (ATC)

Figure 3.



Inviscid Idealization
Figure 4a



Viscous Model

Figure 4b.

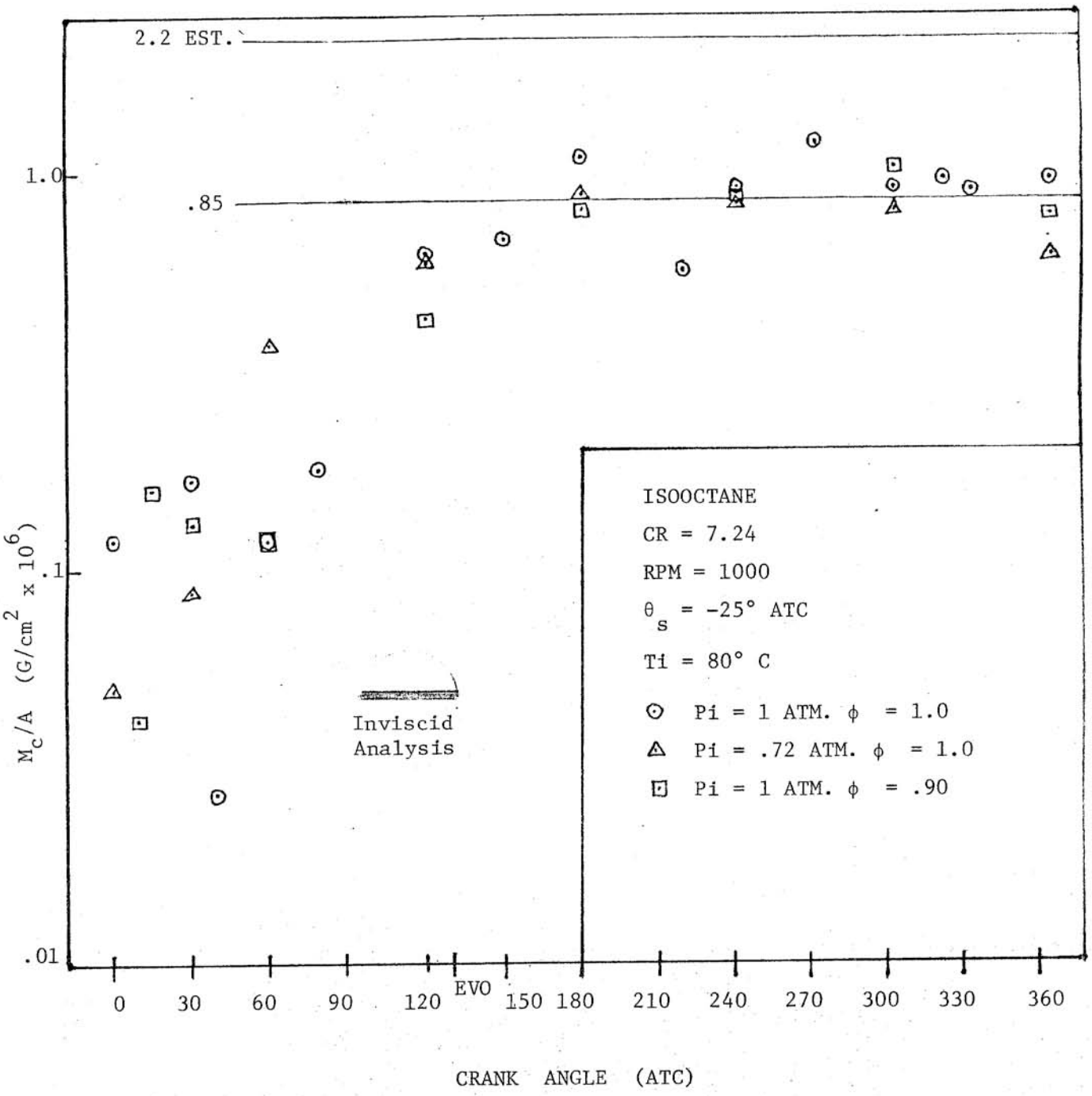

2.2 EST.
1.0
.85
.1
.01
M_c/A (G/cm^2 x 10^6)
Inviscid Analysis
ISOOCTANE
CR = 7.24
RPM = 1000
θ_s = -25° ATC
Ti = 80° C
Pi = 1 ATM. ϕ = 1.0
Pi = .72 ATM. ϕ = 1.0
Pi = 1 ATM. ϕ = .90
0
30
60
90
120
EVO
150
180
210
240
270
300
330
360
CRANK ANGLE (ATC)

Figure 5