AN EXPERIMENTAL INVESTIGATION OF A TOROIDAL ENGINE COMBUSTION CHAMBER

by

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ABSTRACT

An exploratory study of a toroidal engine combustion chamber using a constant-volume bomb is reported in this paper. The toroidal shape design of the combustion chamber studied attempts to achieve continuous fresh air-fresh fuel mixing during injection and obtain desirable rates of air circulation using injected fuel momentum and combustion energy by varying the cross-sectional area of the combustion chamber. High speed photographs of the combustion event were taken for flow visualization. The pressure-time histories of the combustion process was also obtained to characterize combustion and the effects of changes in combustion chamber dimensions, injector position, ignition source, and charge density and temperature. Preliminary results of the experiments undertaken are described.

INTRODUCTION

The design of compression ignition (CI) engines requires effective control of the complex combustion processes to obtain desirable levels of thermal efficiency, engine stresses and vibration, emissions, and fuel sensitivity. Combustion in a CI engine is heterogeneous due to the stratification of the combustible mixture of fuel and air. After the air in the cylinder is compressed by the piston, fuel is injected, atomized, vaporized, and superheated forming a fuel-

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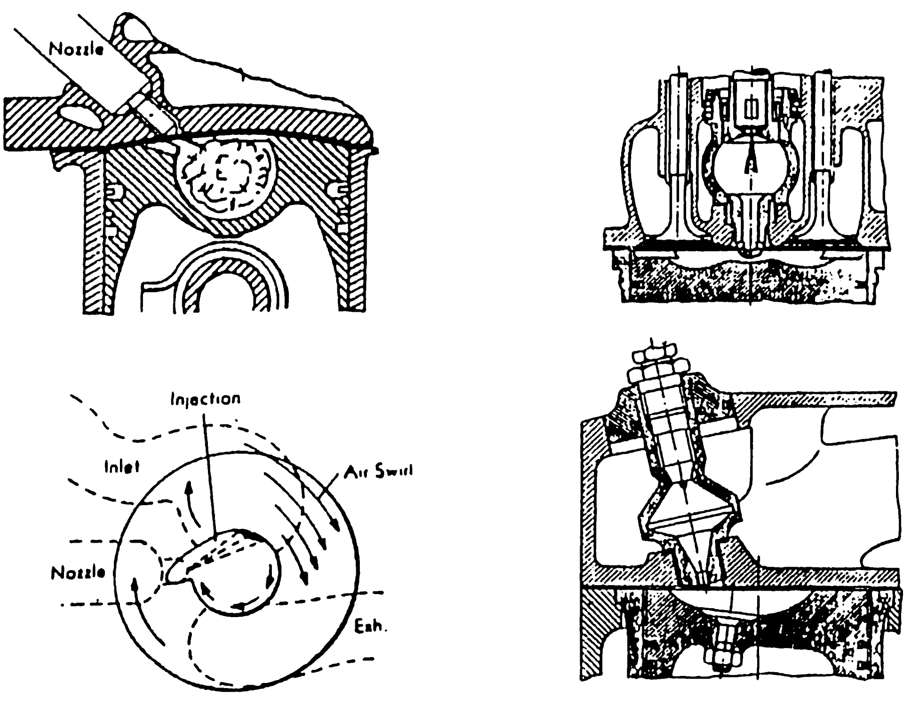
air mixture of varying proportions within the spray envelope (assuming turbulence does not destroy the spray configuration). Rapid (premixed) burning of the accumulated fuel during the ignition delay period occurs afterwards. After the premixed burning period, the combustion rate becomes dependent on the injection rate and fuel-air mixing. The problem of adequate mixing during the short time available, especially in medium to high speed engines, is compounded by the fact that, because of common combustion chamber geometries, fuel is now being injected into partially vitiated air. This condition promotes soot formation, higher hydrocarbon emissions, and more smoke.

In order to control the mixing of fuel and air and achieve desired combustion characteristics in the time available, two general types of schemes are employed in common engine combustion chamber designs.

In direct injection (DI) or open chamber engines, fuel-air mixing is effected by creating initial air swirl and turbulence in the chamber (e.g., through the inlet ports or valves) and injecting the fuel into the air (Fig. 1(a)). The combustion process does not significantly affect the mixing (8). The presence of swirl and turbulence enhance fuel-air mixing before and during combustion due to high rates of mass and momentum transfer between the fuel and air.



(a) (b)

Fig. 1 - Combustion chamber types: (a) open chamber (b)prechamber

In indirect injection (IDI) or prechamber engines, part of the fuel is burned in a prechamber to generate a high pressure mixture of hot vaporizing fuel and rich combustion products, and injecting this into the main combustion chamber at high velocities to produce intense swirl and turbulence (Fig. 1 (b)). The resulting intense swirl and turbulence facilitate the mixing during combustion.

In both the schemes mentioned, fuel is not continuously mixed with fresh air during combustion and in the case of DI engines, the effect of combustion on the mixing process is uncertain.

In this work, an exploratory experimental investigation of a new combustion chamber geometry (Fig. 2) to control the combustion process by controlling the fuel-air mixing was conducted. The chamber was designed to use the injected fuel momentum, combustion, and

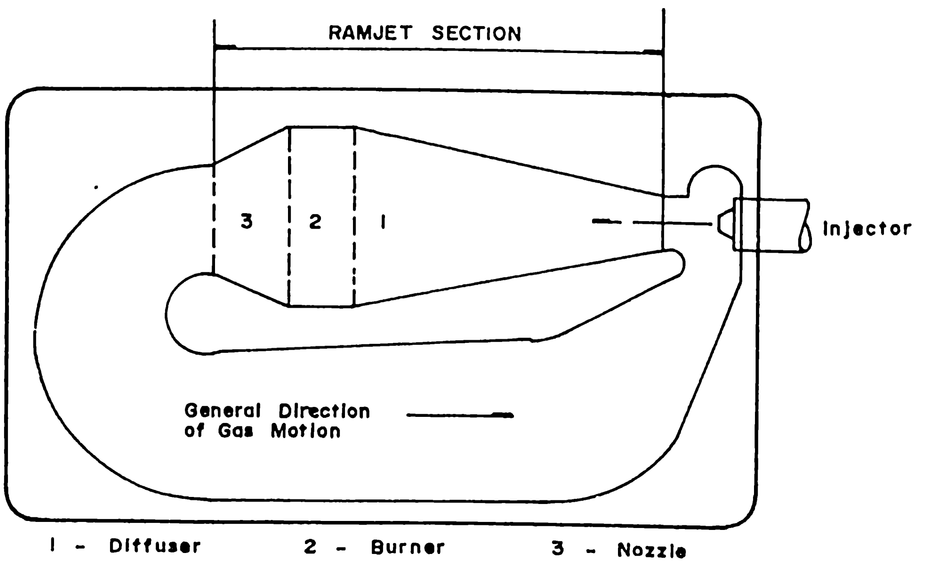


Fig. 2 - Toroidal Combustion Chamber

area variation of the passageways to cause air circulation with the intention of matching the rate of air circulation with the rate of fuel injection. In the envisioned engine configuration (Fig. 3), piston motion late in the compression stroke will also be utilized to generate initial general circulation and local turbulence around the chamber.

The toroidal shape of the chamber and tangential direction of fuel injection assure continuous fresh fuel and fresh air mixing. This configuration also aids in the constructive use of injected fuel momentum to cause air motion in the chamber. The geometry of the section immediately downstream of the injector was shaped like a ramjet to harness both fuel momentum and combustion energy to cause air circulation. By properly dimensioning this ramjet section and the rest of the toroidal chamber using gasdynamics considerations, it was

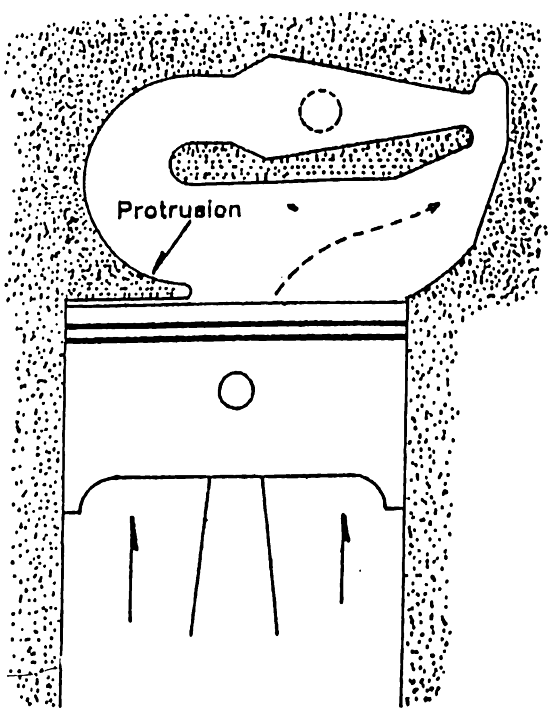
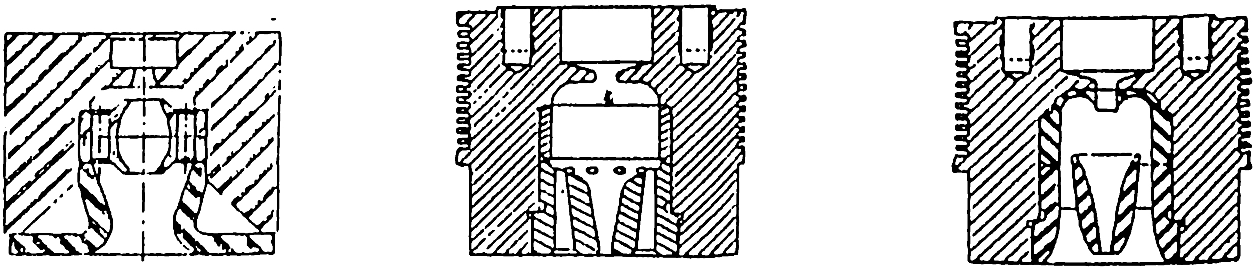


Fig. 3 - Conceived engine configuration

thought that the appropriate amount of circulation in the time available for combustion to obtain desired combustion characteristics would be achieved.

Testing of the toroidal combustion chamber was done using a constant-volume bomb for ease of operation and flexibility. Because of this, the tests performed lack the condition of initial air motion induced by piston motion that will occur in an engine set up. There were no other means employed to generate this initial air motion prior to fuel injection in the experiments . High speed film photography (at 2000 frames/sec) was used for flow visualization. The pressure-time curves of the combustion process were taken to characterize combustion and the effects of various parameters investigated.

The earlier work found dealing with combustion chambers operating on some of the principles used in the chamber design under investigation is that by Kamm and Dragon (2) and continued by Wray and Kamm (10) using a two-stroke diesel engine with replaceable chamber inserts. In their investigation, combustion rate, rate of pressure rise, and peak pressure control in the engine were achieved by "keeping the fuel and air separated in the combustion chamber, except for a small portion of air which is allowed to mix with fuel at a controlled rate to enter into combustion". The separation of fuel and air during combustion was done either by physical means (see Fig. 4(a), dynamic pressure distribution within the chamber (see Fig. 4(b) and 4(c), or a combination of these. Their results seemed to indicate that for the chambers using physical separation, the dimensions of the return air passages were critical for complete combustion over a wide speed and load range. The chambers using dynamic pressure distribution have shown more operational flexibility and better fuel consumption. Also, in the chambers shown in Fig. 4(b) & 4(c), the design of the air and gas flow passages was thought to give maximum dynamic control over the fuel-air mixing rate (10).



(a) (b) (c)

Fig. 4 - Wray and Kamm's combustion chambers

The designs of Wray and Kamm's chambers clearly intended continuous fresh air-fresh fuel mixing and the workers also recognized the need to properly dimension the air and gas passages although there were no explicit methodology or theory suggested. In the present work, gas dynamics and ramjet theory were used to obtain the resulting shapes and sizes of the chambers tested, [Adams (1) and Quiros (5)]. Further, it is an objective to constructively use combustion energy to control air circulation within the chamber, therefore fuel-air mixing. The generation and use of piston motion to generate a unidirectional initial air motion in the chamber is also an objective in the current design. Although there are some similarities between Wray and Kamm's designs and the chamber design in this study, it is believed that the present chamber design can better use combustion energy to control fuel-air mixing and that optimization may be easier due to the approach adopted in designing the combustion chamber.

Combustion Chamber and Experimental Apparatus:

The use of a constant-volume combustion bomb with replaceable ceramic chamber inserts was chosen for the experiments for flexibility in testing various combustion chamber shapes, good optical access, ease of fabrication and operation, and low cost. This approach in combustion chamber investigations has also been used by previous investigators, e.g., Scott (6), White and Wallace (9), and Oren et. al. (4) among others. The combustion bomb body was made of mild steel while the combustion chamber (fitted into the bomb body as a removable insert) was made of fired ceramic. Appropriate holes were drilled into the insert for the glow or spark plug, pressure transducer tap, and manual inlet and exhaust valves. The optical window consisted of two layers, a replaceable 0.25"-thick safety glass or lexan plastic fitted in the top half of the bomb body. The thick window is pressed against the thin one when the bomb body is assembled and tightened.

The toroidal (and "doughnut-like") shape of the combustion chamber was conceived to utilize both physical and dynamic pressure differential separation of the burned and unburned gases. Injected fuel momentum was used to initiate and enhance air circulation by injecting the fuel tangentially into the toroidal combustion chamber. A ramjet-like (diffuser-burner-nozzle) section was constructed immediately downstream of the injector in an attempt to use combustion to generate thrust that will push and circulate the gases around the toroid. Also, a ring type flame holder with a 33%-36% area blockage was initially installed in the diffuser section in an attempt to stabilize and confine the flame within the ramjet section and thus maximize thrust generation. Sizing of the ramjet section, done by Adams (1) and Quiros (5), was estimated from simplified ramjet theory (7). A U-shaped cross-section (0.52" depth) throughout the toroidal chamber was chosen to keep a flat window and for ease of fabrication. The diffuser inlet width was set at 0.375" in all the chamber geometries tested.

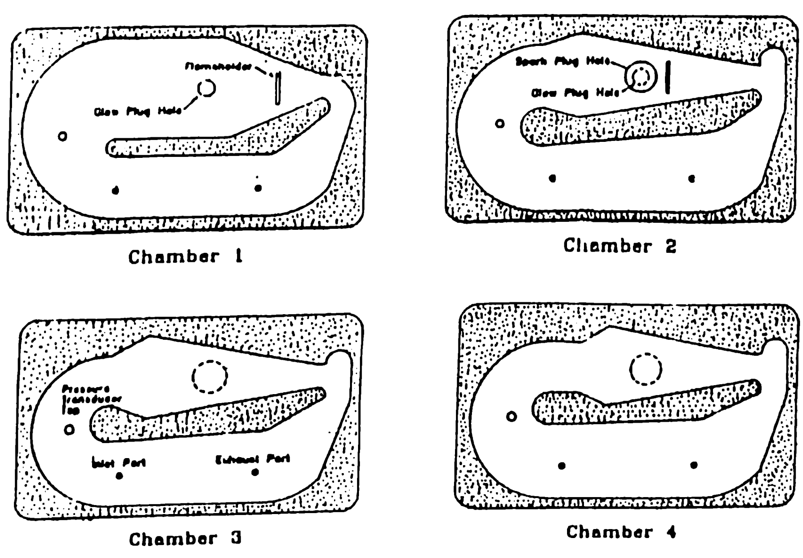


Fig. 5 - Different combustion chambers tested

The total toroidal chamber volume was initially set to be comparable to a cylinder with a 5" bore and 6" stroke and a compression ratio of 17:1. However, design considerations restricted the total volume down to 4.766 to 4.26 cubic inches. Fig. 5 shows the different chamber geometries tested Chamber 1 has a short diffuser section with a relatively larger diffuser outlet area and longer constant-area burner section. The 180-degree turning section after the burner serves as the nozzle. Its total chamber volume is 4.766 cu. inches. Chamber 2 has a longer diffuser section, smaller diffuser outlet, and reduced diffuser angle. Its nozzle section is also shorter. Chamber 2 volume is 4.32 cu. inches. Chamber 3 has almost the same dimensions as Chamber 2 except that its nozzle outlet to diffuser inlet area ratio is reduced to 2.0 (form 2.5 in Chamber 2). Its total chamber volume is 4.26 cu. inches. Chamber 4 has the same nozzle outlet to diffuser inlet area ratio as Chamber 3 but a reduced ramjet section volume. To maintain the same volume as Chamber 3, a constant - area section was added after the nozzle. The burner section in the last three chambers was meant to be a thin region between the diffuser and nozzle sections so that a separate constant-area section between them was not made like in Chamber 1.

The BRM CRIDEC (Common Rail Intensified Direct Electronic Control) fuel system was used in the experiments. It consists of the Fuel Supply Module (FSM), Electronic Control Module (ECM), and the Electronic Unit Injector (accumulator type). A schematic of the fuel system set up is shown in Fig. 6. The FSM provides a high rail pressure supply of fuel to the unit injector while the ECM controls the solenoid valve which activates the injector. The ECM also controls the charging time of the accumulator in the injector and together with the rail pressure determines the amount of fuel injected. The use of the accumulator type injector, with a single 0.406 mm. nozzle orifice, allowed maximum injection pressures of up to 22,600 psi.

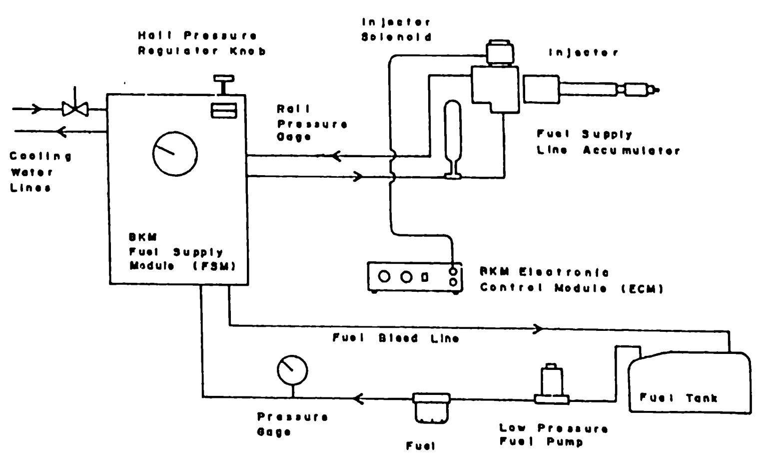


Fig. 6 - Fuel system schematic

Ignition of fuel within the chamber was accomplished using a glow plug when burning with ordinary air (cold combustion) at room temperature. In later experiments, preheating was done prior to fuel injection by mixing air with hydrogen in the chamber and igniting this mixture with spark plug.

A Photec IV 16mm high-speed motion picture camera capable of up to 10,000 frames/sec was used in filming the combustion event. However, only a speed of 2,000 frames/sec was chosen for the experiments. The camera also has a timer and relay which were used in synchronizing the sequence of events when high speed films were taken.

The pressure and injector strain gage signals were recorded with either a Nicolet model 2090 2-channel or model 4094 4-channel digital oscilloscope. Both the signals were stored on 5-1/4 inch floppy disks using either a built-in or accessory disk drive of the oscilloscopes. Data processing was done with a PC using a software specifically made to handle data taken by a Nicolet oscilloscope.

A schematic of the experimental set up with preheating and ignition (of air/hydrogen mixture) using a spark plug is shown in Fig. 7.

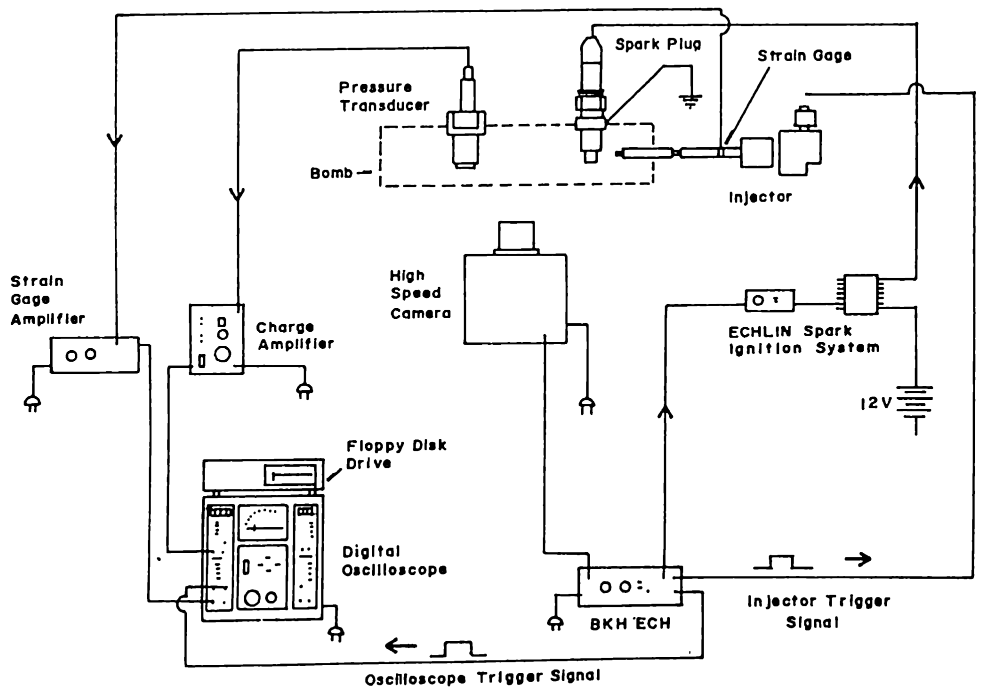


Fig. 7 - Experimental set up with spark ignition

Experimental Procedure and Preliminary Results:

Due to the exploratory nature of the work, various changes in the combustion chamber geometry, ignition system injector position, and condition of the chamber gas prior to injection, among others, were tried to study the effects on combustion, ignition delay, and general gas motion in the chamber. The decisions as to the changers made were based mainly on photographic observations of combustion and the pressure-time records. The procedure followed in the experiments and the qualitative results are discussed below.

Gas motion in the chamber was initially associated with the movement of the luminous front of the burned gas. To measure this movement, the high speed films were projected onto an enlarged drawing of the combustion chamber marked with grids. The luminous front movement was then traced using an analyst projector with freeze frame capability. The grid system used to represent gas motion on-dimensionally is shown in Fig. 8 - the front location is the average of X1, X2, and X3. Zero position was arbitrarily set at the inlet of the diffuser section.

Combustion in the chamber was also evaluated by examination of the gas pressure-time variation. In particular, ignition delay was measured from this data and was defined to be the period from the start of injection to the start of rapid pressure rise. An average of the pressure-time data for several runs under a specified condition was used to characterize the combustion event. These averages, obtained for different conditions, were then compared.

In general, the experiments could be classified as either "cold" or "hot" combustion. In cold combustion, the chamber is filled with ambient temperature (75 F) air to the specified pressure (500 psig). The charge amplifier is then zeroed at this pressure. The glow plug is then heated for 15 seconds after which the injector is manually fired using the BKM ECM. Scavenging of the bomb with compressed air followed while data recorded by the oscilloscope was stored in floppy disks.

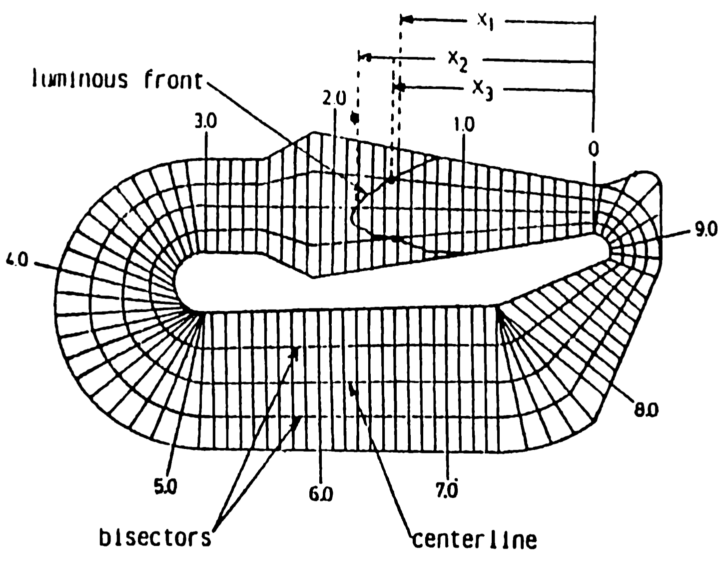


Fig. 8 - Grid system

When filming the combustion event, an electronic timer turns on the glow plug for a set duration and sets the camera delay. After the delay, the camera runs and after a preset footage of film is run, triggers the BKM ECM to fire the injector and the oscilloscope to start taking data.

When preheating is used, the bomb is first filled with the required partial pressure of hydrogen (50 or 65 psig) and then with air until the bomb charge pressure (400 or 500 psig) is reached. A waiting period of about two minutes is provided to allow the gases to mix after which, the BKM ECM is manually triggered to fire the spark plug and trigger the injector and oscilloscope. If filming is done, the BKM ECM is triggered by the camera to complete the rest of the sequence of events.

Variation of Rail Pressure:

Firing of the bomb was done at three injector rail pressures: 900, 1200, and 1500 psi with injection durations of 2.0, 2.9, & 3.5 milliseconds respectively. Better atomization occurred while injected fuel momentum increased with higher rail pressures. The variation of AF ratio with rail pressure for cold combustion is shown in Tables 1 & 2 while that for hot combustion is shown in Fig. 9. The Effective AF Ratio is the AF ratio after complete hydrogen combustion prior to fuel injection.

TABLE 1

Overall Air-Fuel Ratio for 400 psig Bomb Charging Pressure (Ambient Air Only)

Chamber	Rail Pressure (psi)		
	900	1200	1500
2	39.9	25.4	19.1
3	39.4	25.0	18.9
4	39.3	24.9	18.8

TABLE 2

Overall Air-Fuel Ratio for 500 psig Bomb Charging Pressure (Ambient Air Only)

Chamber	Rail Pressure (psi)		
	900	1200	1500
2	49.6	31.5	23.7
3	48.9	31.0	23.4
4	48.7	30.9	23.3

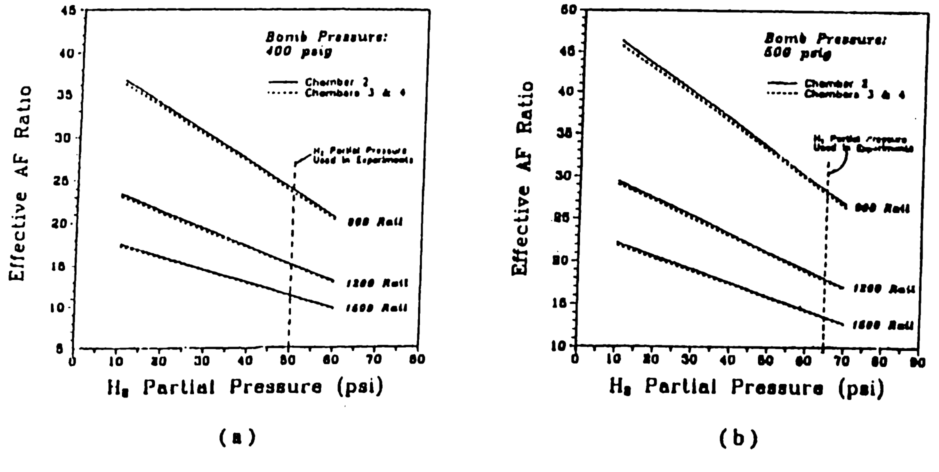


Fig. 9 - Hot combustion Effective AF ratio

Variation of Injector Spacing:

Protrusion of the injector in the chamber was also varied by the use of copper injector gaskets of different thickness. In Chamber 1 test, the injector tip was flush with the chamber wall using a 0.186 inch gasket. In Chamber 2, 3, & 4 tests, either a 0.062 or 0.520 inch gasket was used. With the 0.062" gasket, the tip protruded by 0.124 inch into the chamber while the 0.520" gasket receded the tip by 0.334".

The injector tip position affected the location of the glow plug within the spray. With the thinner gasket, the glow plug was in the less developed region of the spray and thus experienced greater cooling. The AF ratio was also lower. A more fully developed and better atomized spray reached the glow plug with the thick gasket and therefore caused less glow plug cooling. Consequently, it was expected that the ignition delay with the thick gasket would be less. Wall impingement was also seen to occur earlier with the thick gasket.

Variation of Glow Plug Extension and Location:

The amount by which the glow plug protrusion (extension) into the chamber and location relative to the injector tip greatly affected combustion. In Chamber 1 tests, it was found that an extension of 0.30" into the chamber would hardly burn the fuel at 1500 psi rail pressure as shown from high speed films and the pressure traces. Glow plug extension was subsequently increased to 0.48-0.50 inch and the thin window replaced with safety glass (to avoid melting near the glow plug) causing a dramatic improvement in combustion especially at the highest rail pressure. This is attributed to the increased hot spot area making ignition easier and earlier. This glow plug extension was maintained in the remainder of the cold combustion tests.

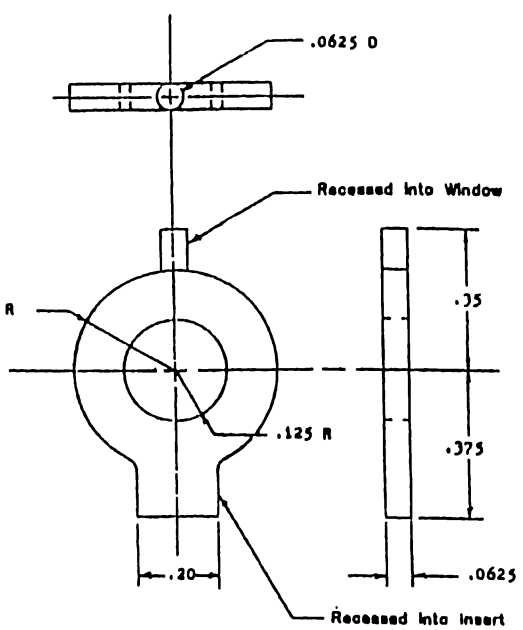


Fig. 10 - Ring type flame holder

Use of Flame holder:

A ring type flame holder shown in Fig. 10 was used in Chamber 1 and in some Chamber 2 tests in an effort to stabilize and confine the flame within the ramjet section. High speed films of combustion showed that the flame (taken to be the luminous portion of the burned gas) extended beyond the ramjet section with or without the flame holder. It was therefore decided to remove the flame holder in the rest of the experiments with Chamber 2, and in all of those with Chambers 3 and 4. Also, it was observed that the flame holder seemed to cause an undesirable restriction to the flow which was critical in Chambers 2, 3, and 4 since the diffuser angle was reduced.

Variation of Fuel:

Two kinds of fuel were tested in the combustion chambers - #2 Diesel only and a mixture of #2 Diesel and Indolene (50/50 by volume). The use of the fuel mixture was an attempt to reduce the ignition delay in cold combustion experiments. However, the differences in the results between the two fuels are not thought to be significant to merit further investigation. #2 Diesel was subsequently used in latter experiments.

Variation of Initial Charge Gas Temperature:

Because of the long ignition delays (2.0 to 4.5 ms) observed with cold combustion such that fuel injection was practically over when combustion started, preheating of the charge gas prior to injection was done. The long ignition delays were detrimental due to the subsequent rapid pressure rise from combustion and also the failure to confine a large extent of combustion within the ramjet section. Hydrogen and air were mixed in the combustion chamber and ignited with a spark plug followed by fuel injection. Preheating in this manner also allowed a better simulation of real engine conditions - the presence of vitiated air. Preheating reduced the ignition delay down to around 0.4 to 0.6 millisecond. The presence of burned gases before injection resulted to richer air-fuel ratios than was previously designed for.

Combustion Bomb Pressure Measurements:

Measurements of the bomb pressure were taken to obtain an indication of the quality and nature of the combustion process. These measurements were used to characterize combustion in terms of ignition delay, peak pressure, pressure rise, and the presence of premixed and diffusion burning. For each given condition, from 4 to 6 runs were performed and the average pressure data calculated. Cycle-by-cycle variation was present in each of the runs.

Cold Combustion

Discussion of the cold combustion results will be limited to Chambers 2 and 3 since no such experiments were done with Chamber 4. The results of experiments with Chamber 1 were deemed unsatisfactory so that only a limited amount of work was conducted with it.

In the following graphs, the **average pressure-time** plots are shown under given conditions. The calculated burned gas volume from film measurements are also included with most of the pressure-time plots to give an idea of its propagation in relation to pressure. It should be kept in mind however that the film measurements although under the same conditions, correspond to a different actual pressure history than the averaged pressures shown with them.

Fig. 11 shows the results using the 0.520" injector gasket (IG) on combustion with Chamber 2. The upper three curves in the figure are the pressure-time traces at various rail pressures (RP) tested. The three lower curves are the corresponding injector signals (not to scale) to indicate the relation between injection timing and bomb pressure change. Injection starts when the signal suddenly drops (after the "horn") and ends when it levels off. The #2 Diesel-Indolene fuel mixture (D/E) was used with the bomb pressure (BP) at 500 psig initial charge.

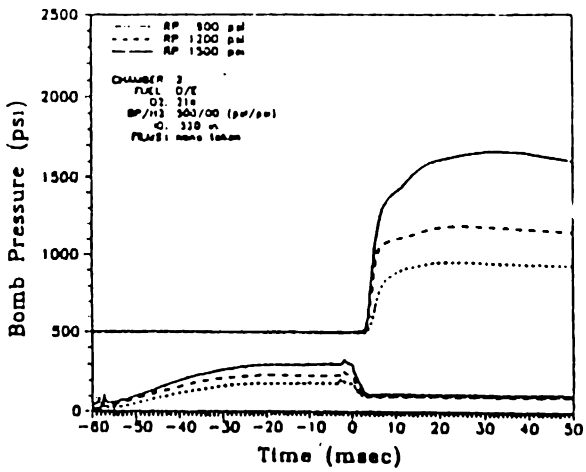


Fig. 11 - Chamber 2 cold combustion, .520" gasket

Because of the long ignition delay, combustion was predominantly premixed with a high rate of pressure rise. A large percentage of the pressure rise occurred during the premixed burning period. The peak pressure is attained at a much later time indicating that combustion was continuing. Although this appears to be "diffusion burning", it will be considered in this work as "**after burning**" since it continues after injection. After burning occurred because of incomplete burning of the fuel in the premixed burning period resulting into a mass of rich combustion products. The likely causes of incomplete premixed burning could be (a) spray wall impingement, (b) insufficient air for mixing due to the physical confinement of the spray in the upper portion of the toroidal chamber, (c) quiescent chamber prior to injection, and (d) the low overall induced gas velocity increase causing low air circulation.

Incomplete combustion was more pronounced at higher rail pressures due to the greater amount of fuel injected. As the mass of rich products flowed around the chamber, the remaining fresh air it encountered together with the inhomogenities within caused further burning. At a later time, the pressure decreased due to diminishing or cessation of combustion and continuing heat loss.

Fig. 12 shows Chamber 2 cold combustion results under similar conditions as in Fig. 11 but with a thin (0.062) injector gasket. The less atomized fuel spray reaching the glow plug also caused greater cooling and resulted to longer ignition delays and poorer combustion. This is suggested by lower peak pressures and rates of pressure rise.

Fig. 13 shows the results with Chamber 3 using the thick injector gasket. The burned gas volume normalized with the total chamber volume (V/Vt)as calculated from film

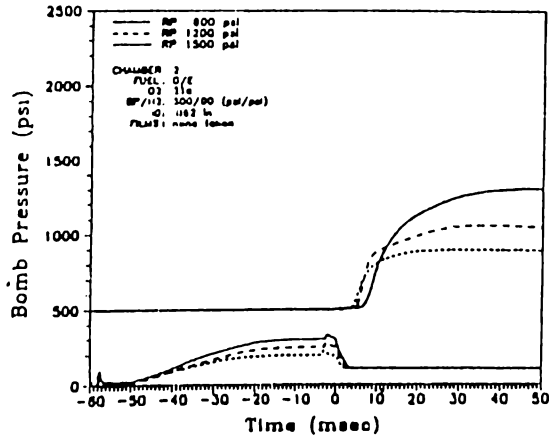


Fig. 12 - Chamber 2 cold combustion, .062 " gasket

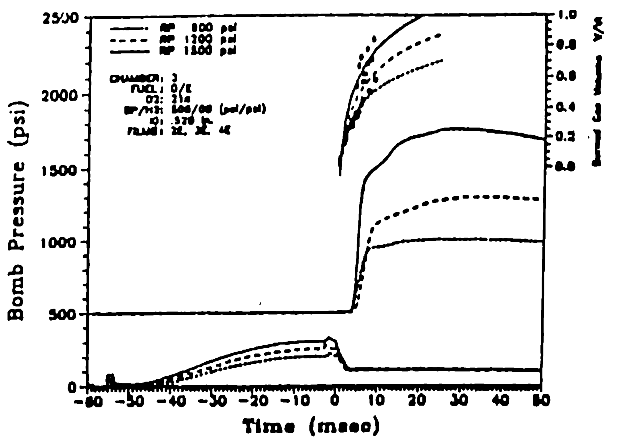


Fig. 13 - Chamber 3 cold combustion, .520" gasket

measurements and fitted with logarithmic curves are also shown with the pressure plots. Similar processes as in Fig. 11 are suggested although slightly higher pressures and pressure rise are seen with Chamber 3.

In terms of the cold combustion results, there are no significant differences between Chamber 2 and Chamber 3.

Hot Combustion:

Most of the experiments were performed with preheating by hydrogen combustion to reduce ignition delay (to 0.6 ms average) and to better simulate engine conditions. In the succeeding discussions, comparison of the different chamber configurations tested will be based on the pressure rise P-Rise due to fuel combustion (or heat release) taking into account bomb conditions at injection.

The bomb pressure Po at the start of injection varied due to cycle-by-cycle variation in hydrogen combustion. The same pressure rise occurring at different initial bomb pressure (Po) will correspond to different heat releases due to the variation of specific heat with temperature. However, calculations made by Quiros [5] showed that these differences are small (in the range of Po seen experimentally) and thus can allow direct pressure rise comparison.

To illustrate the more important findings, only some of the results for Chambers 2 & 3 will be presented. The conditions of the runs to be discussed are shown in Tables 3, & 4. The columns give the following data respectively: 1-Run (label), 2-Chamber #, 3-BP/H2 (bomb charge pressure/hydrogen partial pressure, psi/psi), 4-Fuel used (#2D for #2 Diesel only and D/E for Diesel-Indolene mixture), 5-IG (injector gasket, inch), 6-Rail pressure (psi), 7-Pmax (peak bomb pressure, psi), 8-Po (bomb charge pressure, psi), 9-P-Rise (pressure rise due to fuel combustion).

TABLE 3
Chamber 2 Test Conditions

RUN	CHAMBER	BP/H_2	FUEL	IG	RAIL	Pmax	Po	P-Rise
A3	2	400/50	D/E	.062	900	1359	753	606
B3	2	"	"	"	1200	1522	728	794
C3	2	"	"	"	1500	1692	691	1001
A4	2	500/65	D/E	.062	900	1663	1226	437
B4	2	"	"	"	1200	1972	1184	788
C4	2	"	"	"	1500	2076	1144	932

TABLE 4
Chamber 3 Test Conditions

RUN	CHAMBER	BP/H_2	FUEL	IG	RAIL	Pmax	Po	P-Rise
D1	3	400/50	#2D	.062	900	1540	1017	523
E1	3	"	"	"	1200	1669	1028	641
F1	3	"	"	"	1500	1808	1079	729
D2	3	400/50	#2D	.520	900	1484	951	533
E2	3	"	"	"	1200	1652	979	673
F2	3	"	"	"	1500	1789	1043	746

Fig. 14 shows the results for Runs A3, B3, C3 in Table 3. Because of the short ignition delay, combustion is more diffusion-like. The steep slope of the pressure curves suggests high rates of diffusion burning during injection after which it decreases. The post injection pressure also shows after burning which again signifies incomplete combustion in the ramjet section

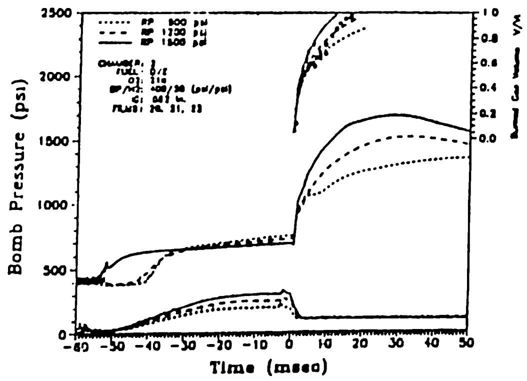


Fig. 14 - Runs A3, B3, C3

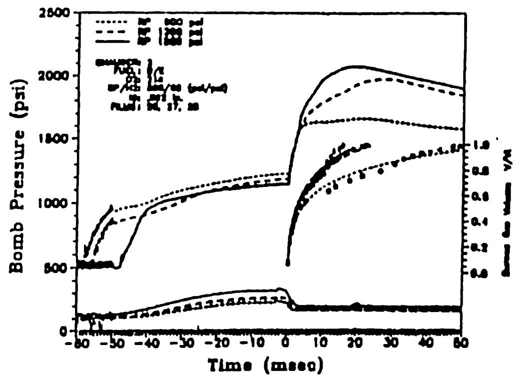


Fig. 15 - Runs A4, B4, C4

during injection. The after burning slope is lesser at lower rail pressures due to lower amounts of injected fuel.

The occurrence of the pressure peak at approximately the same time at higher rail pressures is interpreted to signify a higher burned gas circulation rate at higher rail pressures thus increasing combustion rates. The film measurements seem to agree with this. Increased injected fuel momentum at higher rail pressures and probably combustion could increase circulation rates.

Fig. 15 shows the results (Runs A4, B4, C4) at a higher bomb charge pressure with a corresponding increase in hydrogen partial pressure. The peak and initial pressures are higher than those runs at lower charging pressures. The pressure rise in Runs A4, B4, C4 is lower than for Runs A3, B3, C3. This seems to indicate that the burned gas circulation rate could be faster with the lower bomb charge pressure because of the lesser mass of gas; a lesser mass has lower inertia and therefore moves faster for the same imparted momentum from the fuel. Comparison of the burned gas volume curves likewise show faster movement at the lower charge pressure. The lower overall air-fuel ratio with Runs A3, B3, C3 might have slowed down the completion of burning so that the peak pressures occur later than those with Runs A4, B4, C4.

Another significant observation from the pressure data obtained from the tests is the higher pressure rise achieved with the thick than the thin injector gasket when the bomb is run under comparable conditions. This is illustrated in the comparison between Runs D1, E1, F1 and Runs D2, E2, F2 and shown in Figs. 16 & 17. The consistency with which this was observed in the experiments with Chambers 2, 3, & 4, whether cold or hot combustion, strongly confirms the role of better atomization in producing a higher pressure rise from combustion.

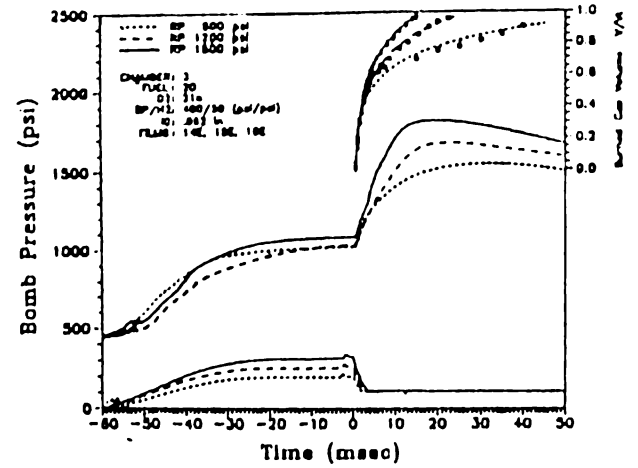


Fig. 16 - Runs D1, E1, F1

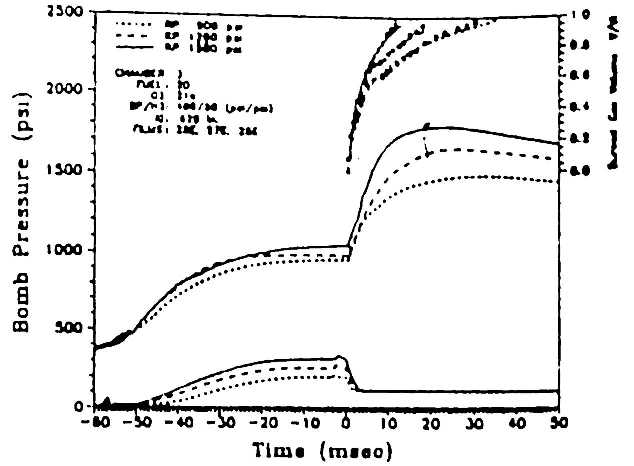


Fig. 17 - Runs D2, E2, F2

Comparison of Chambers 2, 3, & 4:

Pressure rise is generally highest in Chamber 2 among the chambers. Chamber 4 gave lower pressure rise than Chamber 3. The results seem to indicate that the less restrictive to the initial flow the early sections of the toroidal chamber are, the higher the pressure rise obtained. It is not clear why this is so but the geometry of the ramjet and the adjacent downstream sections could have caused notable differences in the fluid flow and burned gas propagation in the chambers. These differences resulted to varying combustion characteristics especially with regards to the extent of after burning that ensued. However, the differences noted in the pressure rise are not deemed significant so that the performance of the chambers is viewed as approximately similar.

Observations and Discussion:

It was observed from the film measurements, Quiros (5), that the burned gas volume curves representing luminous front propagation was relatively high in comparison with the pressure rise early in the combustion process. This is taken to signify that the luminous front speed is higher than the actual gas speed during this period. Thus, the luminous front propagation may not indicate reasonably the gas speed especially early in the combustion process as previously thought Quiros (5). This is believed to be due to the imperfect momentum transfer between the burning spray and the chamber gas so that the spray penetrates through the unburned gas. In this sense, the luminous front behaves as a propagating "porous" membrane. The after burning observed in the pressure traces is also thought to suggest similar behaviour since fresh air entrainment (as the burned gas mass flows around) is necessary to sustain further burning. Since after burning accounts for about 1/2 to 2/3 of the total pressure rise seen in the results, it is a significant portion of the combustion process in the toroidal chambers under the conditions of the tests. It is believed that the extent of after burning may be reduced with the presence of initial air swirl in the chamber such as will be produced by the upward motion of a piston.

Conclusions:

An exploratory work on a toroidal engine combustion chamber that attempts to control fresh fuel-fresh air mixing to obtain desired combustion characteristics was constructed and tested. Different chamber configurations were tested using a constant-volume bomb and the performance evaluated from pressure-time data and high speed film photography for flow visualization.

Analysis of the data indicates that a) a better atomized spray entering the combustion chamber and/or b) the use of lower charge densities result to higher pressure rise (which is taken to show more complete combustion). Also, after burning is a significant portion of the combustion process indicating the need for initial air swirl in the chamber if combustion is to be completed in a shorter time. The propagation speed of the luminous front, especially early in the combustion process, does not reasonably indicate actual gas speed.

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