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PERFORMANCE OF MULTIPLE STREAM PULSED JET COMBUSTION SYSTEMS

By

J. A. Maxson, D. M. Hensinger,
K. Hom, and A. K. Oppenheim

University of California
Lawrence Berkeley Laboratory
Berkeley, California 94720

ABSTRACT

In the course of our studies on pulsed jet combustion (PJC) a series of tests were carried out to determine the performance of multi-stream systems. This included multi-jet efflux, as well as dual-generator aggregates. The essential performance indicator of a PJC system is the pressure transducer record, yielding, in particular, data on the rise time and amplitude of the pressure pulse, as well as the rate of pressure rise. Concomitantly with pressure measurements, a sequence of schlieren records were obtained to reveal the salient features of the fluid mechanical phenomena of the PJC process. Elucidated thereby are the effects of entrainment induced by large scale vortex structures of turbulent jet plumes, and their decisive role in governing the process of combustion, as influenced by their particular configuration. Our tests demonstrated the capability of multiple stream PJC systems to shorten the rise time and increase the amplitude of the pressure pulse, both effects of obvious potential benefit to engine performance.

PRESENTED HERE is a progress report on our studies of pulsed jet combustion (PJC), a highly turbulent system of particular relevance to advances in engine technology. Its performance is quite different from that of the conventional flame traversing the charge (FTC), as demonstrated in our previous publications [1,2]. The fundamental reason for this is that, unlike the flame which, in its broadest sense, is a zone of demarcation between the burnt and unburnt medium, in a PJC plume the combustion process is distributed, so that such a distinction cannot be made. At its active stage, what appears as burnt in the plume is actually still burning. The exothermic chemical reaction is then spread out in space and prolonged in time, a circumstance of obvious advantage to the progress of the combustion process.

The concept of PJC has an interesting history. It has been the subject of about half a century of studies conducted at the USSR Academy of Sciences Institute of Chemical Physics under the personal guidance of N. N. Semenov, its director and the Nobel Prize laureate for founding the chain reaction theory. This lead to the development of the so-called *Torch Ignited LAG* (Lavinnaia Aktyvatsia Gorenia or Avalanche Activated Combustion) *Process* realized in an engine that had the attribute of operating without knock at a relatively high compression ratio, using gasoline of an octane number in the seventies. Based on the fundamental background provided by Semenov [3,4], this project included the contributions of Gussak [5-11] and Karpov [6,9,12] and their associates, as well as of such luminaries as Sokolik [12] and Zeldovich (vid. [10]). The engine has been mass produced by the Gorki Automobile Factory (Gorki Avto Zovod or GAZ) and it provided service for decades in trucks, having been eventually incorporated into the power train of the Volga sedan [13].

The then so-called Gussak's LAG engine has been often confused with the Honda CVCC (*Compound Vortex Controlled Combustion*) [13]. Both are three-valve, divided-chamber, stratified-charge engines. There exists, however, a fundamental difference between the two. In the Honda case, a turbulent flame emerges out of the pre-chamber and propagates without interruption into the cylinder. In the LAG process, as well as in a PJC system, combustion is extinguished by shear at the exit of the orifice. Ignition of the charge takes then place inside the turbulent plume made out of large scale vortex structures formed by shear generated by the jet at the efflux. Thus, paradoxically enough to confuse the issue, the Honda system features a *propagating torch*, while the LAG process involves, in effect, a *vortex controlled combustion*, the essential property of a PJC system.

The extensive investigations conducted at Semenov's Institute revealed the profound effects of chemical kinetic processes associated with subdued influence of molecular transport phenomena. Our studies are prompted by the realization that PJC offers an attractive potential as an active element for controlling the process of combustion in engines [14,15]. To complement the knowledge on chemical aspects acquired with the development of the LAG process, primary emphasis is placed this time upon the fluid mechanical phenomena.

Our previous studies of the PJC system have been published in two papers. In the first [1], we have demonstrated the remarkable superiority of PJC over the conventional FTC system for initiating and propagating

the process of combustion in highly diluted mixtures. In the second [2], we showed that the PJC process consists of three stages: *the jet, the plume, and the puff*. The first is the formation of a jet plume, a purely fluid mechanical process devoid of the exothermic effects of chemical reaction. The reason for this is as follows. *The jet* issuing from the orifice consists of high temperature products of incomplete combustion which have to be mixed with oxygen in the charge before they can burn. The mixing is impaired by the shear at the exit from the orifice. There is, therefore, a significant time delay in the onset of combustion during which the flow field is de facto non-reacting. *The plume* is the most active stage of the system where vigorous combustion of entrained charge takes place within the large scale vortex structures of a turbulent field. *The puff* is a turbulent cloud of products surrounded by a flame front. It arises when combustion of the entrained charge is completed. The PJC system becomes then transformed into a turbulent FTC. It is thus the stage of the plume that governs the performance of a PJC system.

Salient features of the formation and structure of a turbulent jet plume are described in Fig. 1, a graphical output of numerical studies carried out by the use of Chorin's random vortex method [16]. Brought out here are all the characteristic features of large scale vortex structures and the concomitant mechanism of entrainment.

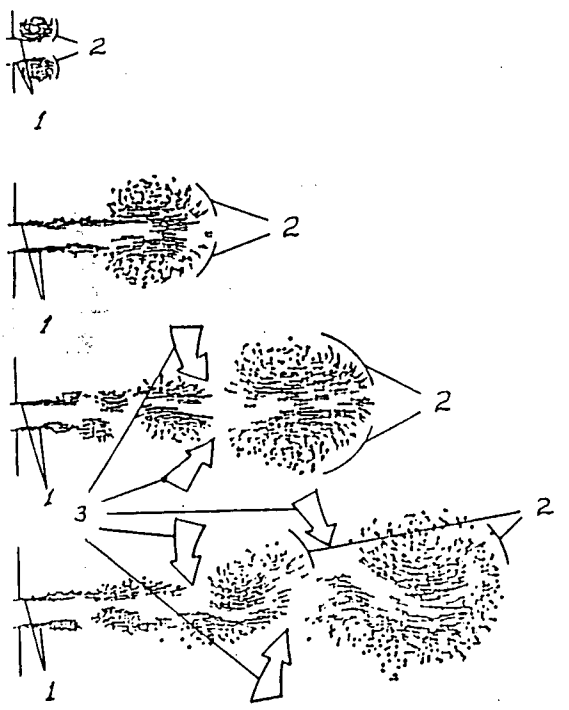

Fig. 1 Formation and Structure of a Turbulent Jet Plume
1-zones of intense shear with stretch and extinction; 2-cores of large scale vortices, the most likely place for the exothermic process of combustion to occur; 3-pathways of entrainment.

Presented in this paper are the results of tests carried out to investigate the performance and fluid mechanical features of multi-stream PJC systems with respect to their effectiveness as combustion control elements. Included among them are a multi-orifice efflux and dual-generator aggregates, the latter in its most elementary form of two, simultaneously activated, opposed jets. The essential performance indicator is the pressure transducer record, the actual evidence of the exothermic nature of combustion. Of special significance in this respect are the rise time of the pressure pulse, its amplitude, as well as the rates of pressure rise. The evaluation of the latter demands particular precision in the measurement of the pressure pulse and its numerical treatment. As the major objective of our studies is concerned with the mechanism of the turbulent flow field generated by the jet, the experimental tests are performed in a constant volume vessel where the combustion mixture is initially at rest. Reasons why this is appropriate for this purpose are brought out in the last section of the paper.

APPARATUS

The PJC generator used in this investigation is a miniaturized version of the valve-operated pre-chamber of Gussak [5]. It was developed by us following the evolution of the swirl-chamber spark plug devised by Latsch [17]. Its salient features are depicted in Fig. 2.

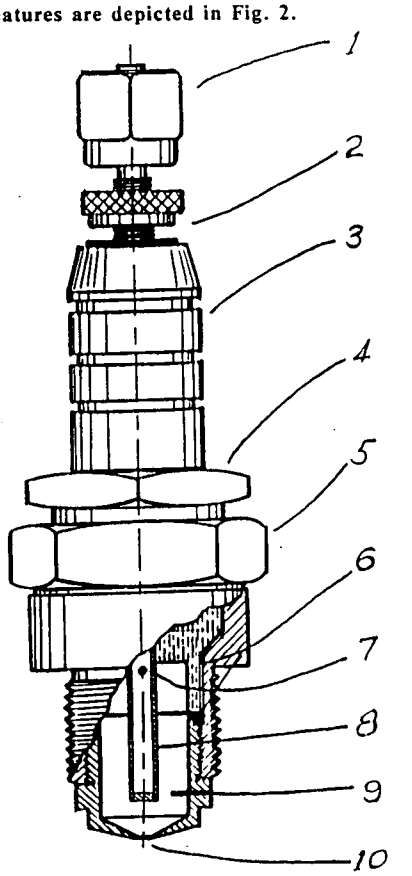

Fig. 2 PJC Generator
1-tube fitting; 2-high voltage terminal; 3-insulator body; 4-retainer nut; 5-plug body; 6-O-ring gaskets; 7-inlet port; 8-hollow electrode; 9-ground electrode; 10-ejector tip with a discharge orifice.

The major refinement of the unit is associated with the reduction in the volume of the cavity from 1.3 cm^3 to 0.5 cm^3. As a consequence, it can be accommodated now in a 14 mm ignition plug, in contrast to the 18 mm fitting we used before [1]. As in the previous version, the high voltage electrode is made out of a nickel tubing to provide a conduit for admitting the charge of a pre-carbureted, rich, air/fuel mixture into the cavity. For this purpose the wall of the hollow electrode is perforated close to its entrance at the closed end of the cavity to assure its good scavenging. The pre-chamber is formed by the tip which is screwed in from the open side of the plug to secure a seal with the insulator body on the inside and provide an orifice plate at its outer end. The tip is fitted with a thin tungsten rod at its wall in the immediate proximity of the orifice to serve as the ground electrode. The process of combustion is thus initiated close to the exit to assure that the jet consists mainly of combustion products.

The intensity of turbulence in the jet plume depends on the size, number, and orientation of the orifices, as well as on the rate of pressure rise in the cavity. Of particular importance in this respect is the time interval between charging the cavity with the air/fuel mixture and the spark discharge for ignition - a parameter that for proper operation must be electronically controlled. To achieve reliability and repeatability of the single pulse tests we ran, the cavity of the PJC generator was filled by the use of a specially devised, pneumatically operated, piston charger described in Fig. 3. In an operating engine this would be accomplished, of course, by a much faster acting, solenoid activated valve system.

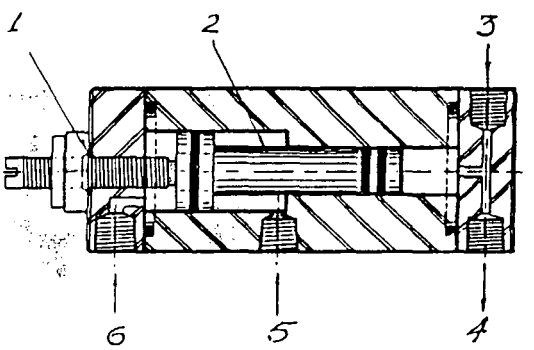

Fig. 3 PJC Cavity Charger
1-stroke adjustment mechanism; 2-pump piston; 3-check valve controlled inlet from mixture reservoir; 4-check valve controlled outlet to generator cavity; 5-vent; 6-solenoid controlled valve for compressed gas to push the piston.

Experimental tests were carried out in a cylindrical vessel of 8.26 cm bore (same as a standard CFR engine) and 5 cm width, providing a volume of ~ 280 cm^3 (head space in a CFR engine with compression ratio is 7.5:1 at 60 CAD), and is equipped with 5 cm thick optical quartz windows for schlieren photography, as well as a thermocouple and pressure transducer [1]. In operation, the test vessel is wrapped with an electrical heating tape to maintain it at an elevated temperature.

PROCEDURE

The primary purpose of our investigation is to examine the performance of a variety of PJC systems. In recognition of current technological standards, a comparison with the conventional FTC system is included, for it is the fundamental difference in the *mechanism* of the two systems that is in this respect of particular interest. In order to bring this out, our tests were run in a quiescent mixture at a lower pressure and temperature than those encountered in engines. The time scale was thus stretched by about an order of magnitude.

As pointed out in the introduction, the primary diagnostic indicator in our studies was pressure in the test chamber. This was measured by a Kistler 603B1 acceleration-compensated, piezo-electric transducer with high-impedance charge-signal output, using Model 504E dual mode amplifier. The natural frequency of the system was over 500 kHz. The signal was recorded by the use of a Hewlett Packard 54111D digitizing oscilloscope, providing a 2 gigasample per second digitizing rate in a 500 MHz band width. To observe the mechanism of the flow field under study, a conventional, Z-configuration, double-mirror, schlieren system was used, employing an EGG light source consisting of Model PS302 Power Supply, FY-903 Trigger Module, and FX-800 Xenon flash lamp.

The digitized pressure transducer records were processed numerically. The signal was first low-pass filtered by truncation of its Fourier transform to remove the high frequency noise. It was then expressed in terms of a polynomial by linear regression. A 20 order fit proved to guarantee a below 1% deviation from the data. This was used then to evaluate the rate of pressure rise by straightforward differentiation.

OPERATING CONDITIONS

Performance tests were carried out of four PJC systems:

1. single orifice, single generator
2. triple orifice, single generator
3. single orifice, double generator
4. triple orifice, double generator

To assess relative merits, their performance was compared to conventional single spark and double spark FTC systems.

In all the cases, propane air mixtures were used, delivered from storage tanks where they were prepared by partial pressures. The equivalence ratio in the test vessel was 0.6, while in the cavity of the PJC generator it was 1.5. The initial pressure was 5 atm and the temperature was 65°C. Combustion in the cavity was initiated by spark discharge from a conventional automotive ignition coil at 35 kV. With a fixed cavity volume and charging technique, there are two critical parameters governing the operation of a PJC system:

1. orifice size, and
2. time delay between triggering the charger and ignition.

For a cavity of 0.5 cm^3, the optimum cross-section was found to be 5 mm^2, which for a single orifice corresponds to 2.5 mm in diameter and for a triple orifice to 1.44 mm. The charging technique we used was developed especially to make sure that the cavity is filled homogeneously with the prescribed mixture, while the overflow into the test chamber is practically negligible. The motion of the charger piston was, therefore, quite slow, taking approximately 13 msec. Under such circumstances, the optimum time delay between the signal

to activate the charger piston and ignition was found to be 15 msec. The tests whereby these values were established are described in the next section.

RESULTS

General

The results are presented here in a systematic manner. For each case, displayed first is the pressure pulse and its time derivative, the rate of pressure rise. In all the diagrams the origin of the time scale marks the instant of spark discharge. To assure reproducibility, each test was performed four times. The graphs present their average values. Each subsequent case is presented by continuous lines in comparison to a previous one depicted by broken lines.

The salient features are expressed in terms of the following performance parameters:

1. pressure rise time - the time interval between the moment when the pressure rise becomes positive and when it falls down to zero at the maximum pressure.
2. maximum pressure - the amplitude of the pressure pulse.
3. maximum rate of pressure rise - the slope of the pressure pulse at the point of inflection.
4. effective rate of pressure rise - the slope of the pressure pulse most indicative of the performance of a PJC plume. The reason for introducing this parameter was the fact that the maximum rate of pressure pulse occurs at the stage of the passive puff, rather than that of the active plume. Under the particular conditions of our tests, the effective rate of pressure rise turned out to be simply the slope of the pressure pulse 10 msec after the spark discharge.

These parameters, together with their standard deviations, are presented in the table. Each system we tested is expressed there in terms of its characteristic features. The first four entries refer to a single orifice generator, each case identified by the orifice diameter and the time delay. The table lists the values of all the parameters, as well as the standard deviation of the data used for their calculation. The error, or the mean departure of the data from the listed average, is, of course, half the deviation. Except for the effective rate of pressure rise in the exceptional case of 2.5 mm diameter and 20 msec time delay and the maximum rate of pressure rise, which, as pointed out above, is of no relevance to the performance of the plume, all the parameters are getting better in the sequence in which they are listed.

Associated with pressure measurements is a set of flash schlieren records of the combustion field. The graphs provide thus specific information on the essential effects of the exothermic process of combustion, while the photographs offer an insight into the fluid mechanic features of the turbulent flow field under study.

Pressure Pulse Parameters

System	t_{rise} msec	p_{max} atm	$\left(\frac{dp}{dt}\right)_{max}$ atm/ms	$\left(\frac{dp}{dt}\right)_{eff}$ atm/ms
6 mm	119.3	19.05	0.236	0.038
15 ms	2.8%	0.8%	4.8%	4.6%
4 mm	107.1	19.54	0.228	0.071
15 ms	3.7%	1.7%	5.9%	0.2%
2.5 mm	107.3	18.73	0.166	0.136
15 ms	4.8%	1.3%	10.4%	4.5%
2.5 mm	102.5	19.17	0.235	0.075
20 ms	1.9%	0.7%	11.8%	13.2%
Triple	82.4	19.82	0.292	0.149
1 PJC	4.0%	0.5%	3.9%	7.8%
Single	73.0	20.30	0.289	0.227
2 PJC	1.7%	0.9%	2.3%	1.5%
Triple	64.6	20.03	0.398	0.354
2 PJC	6.5%	1.4%	5.0%	6.6%
Single	260.8	16.00	0.064	0.000
FTC	0.9%	0.3%	2.8%	0.0%
Double	179.0	18.19	0.152	0.005
FTC	1.7%	0.7%	1.2%	7.5%

Single Orifice System

In order to establish the optimum orifice diameter and the time delay, i.e. the time interval between activating the cavity charger and ignition, a series of tests were run with different orifice diameters and two time delays. Presented in Fig. 4 are pressure pulses and their time derivatives for orifice diameters of 6, 4, and 2.5 mm,

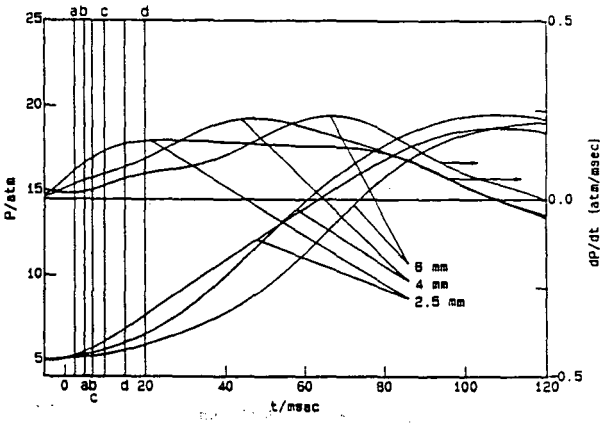

Fig. 4 Pressure Pulses of Single Orifice PJC Systems
Orifice diameters: 2.5, 4 and 6 mm.
Time delay: 15 msec.

while the time delay was 15 msec. This turned out to be the critical time for the operation of the 6 mm case; just enough to fill the cavity and not too long to have its charge diluted by infusion from the test chamber. The corresponding schlieren records are shown in Figs. 5 and 6.

With the 6 mm orifice the cavity is *de facto* open-ended. The maximum pressure and its rise time are lower than those of the 4 mm orifice. As manifested in Fig. 5, the PJC system in this case has a character of a *puff* rather than a *plume*, that is a turbulent cloud of burned gases bounded by a flame front - a system devoid of any effects of entrainment. Under such circumstances the process is akin to the Honda CVCC rather than Gussak's LAG. The 4 mm case displays already the characteristic features of a plume, as demonstrated in Fig. 5.

In a regular progression from 6 and 4, one would expect a 2 mm orifice diameter. We have found, however, that, the operation of the system became then unreliable, an effect due indubitably to excessive quenching of the jet

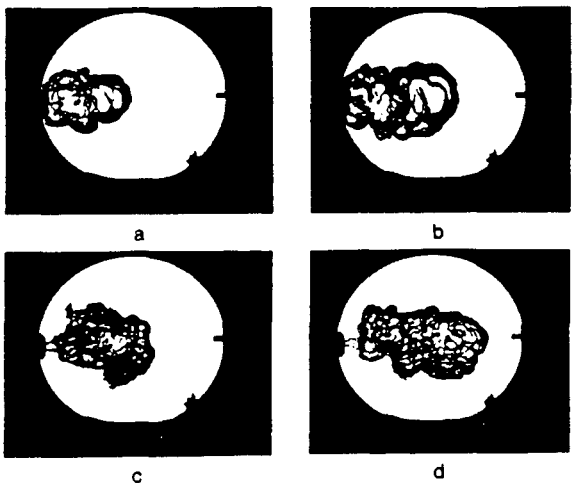

Fig. 5 Schlieren Records of Single Orifice PJC Systems
Orifice diameters: a&b: 6mm; c&d: 4mm;
Time delay: 15 msec
Times of records denoted by vertical lines in Fig. 4 marked at the bottom.

at the exit. Thus the minimum diameter at which our PJC would operate satisfactorily was 2.5 mm. The pressure pulse for this case, shown in Fig. 4, is quite surprising. Following a remarkably fast start, the rise time of the pressure pulse is excessively long and its amplitude is relatively low, the rate of pressure rise reaching a plateau at a comparatively low level. The reason for this odd outcome is revealed in Fig. 6. The

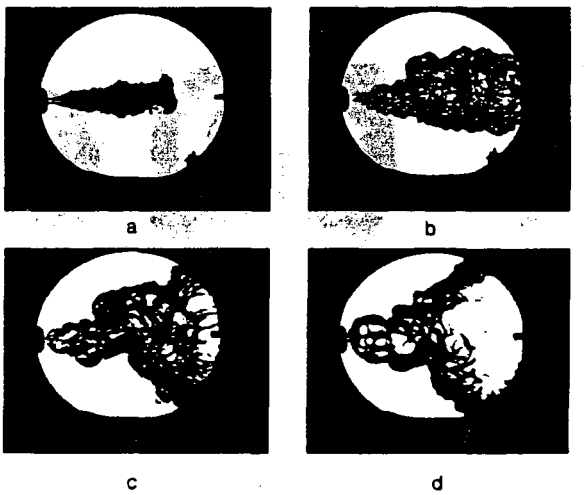

Fig. 6 Schlieren Records of a Single Orifice PJC System
Orifice diameter: 2.5 mm
Time delay: 15 msec.
Times of records denoted by vertical lines in Fig. 4 marked at the top.

initial momentum of the jet and the penetration of its turbulent plume, with the concomitant entrainment manifested by the mushroom shape of its front, apparent in segment a, were then evidently so large that the stream reached the opposite wall exceedingly fast. Wall effects were in this case detrimental for two reasons. First, they were the primary cause of heat loss, affecting detrimentally the pressure amplitude [18]. Secondly, what was here of particular significance, they produced a stagnation zone that terminated the action of the plume with its ability to propagate combustion by entrainment, replacing it by the significantly less effective FTC mode, as clearly evident in segment d.

In order to check the validity of this interpretation, tests were run for the same PJC generator with a time delay of 20 msec. The results are presented in Figs. 7 and 8. All the salient features of the power pulse have been significantly improved as demonstrated by comparison to the previous case presented by broken lines, while, as

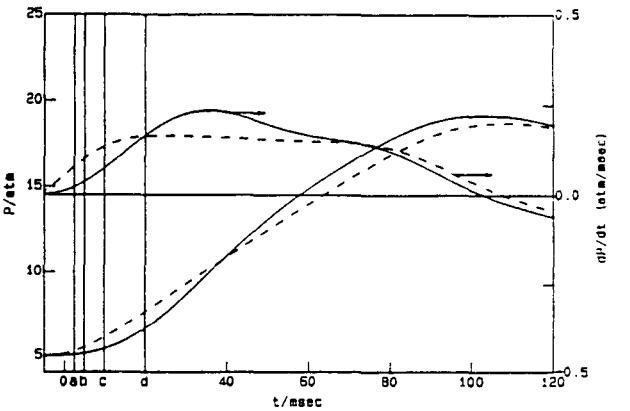

Fig. 7 Pressure Pulses of Single Orifice PJC System
Orifice diameter: 2.5 mm
Time delay: 20 msec.

illustrated in Fig. 8, the contact between the plume and the wall, with its detrimental consequences, has been distinctly reduced.

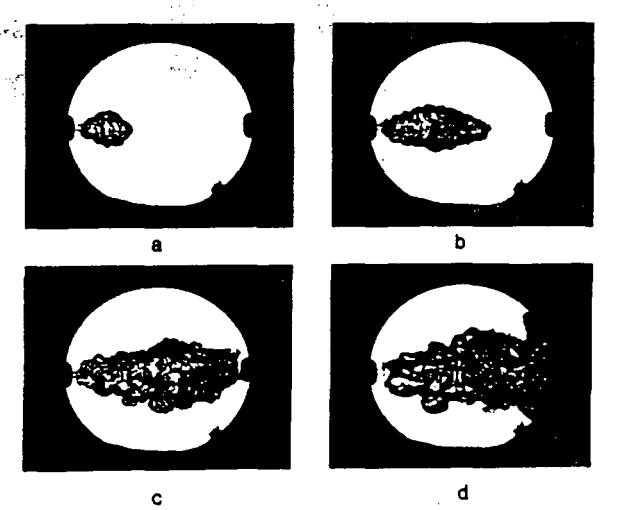

Fig. 8 Schlieren Records of a Single Orifice PJC System
Orifice diameter: 2.5 mm
Time delay: 20 msec
Times of records denoted by vertical lines in Fig. 7.

All the subsequent cases reported were run with both 15 msec and 20 msec time delays. The shorter times produced consistently somewhat better performance, but the difference was not remarkable. Thus, for the sake of brevity, presented here are solely the results obtained with the shorter time delay.

Triple Orifice System

The performance of a triple orifice system, with the three holes lined up in parallel to the side walls, delaying thus their exposure to burnt gases, is better than that of a single orifice unit, as demonstrated by the pressure plots of Fig. 9 in comparison to those of Fig. 4. The

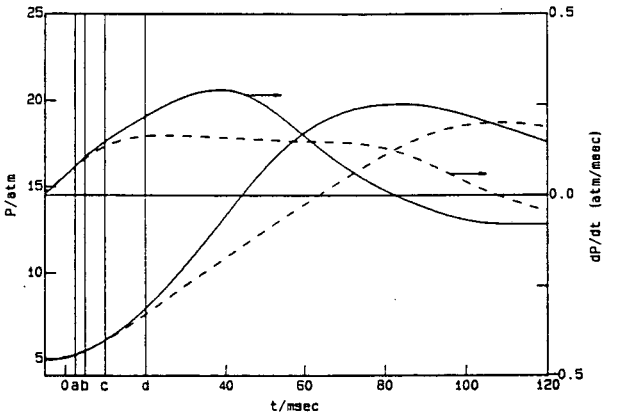

Fig. 9 Pressure Pulse of a Triple Orifice PJC System
Orifice diameters: 1.44 mm
Time delay: 15 msec.

corresponding schlieren records are presented in Fig. 10, illustrating clearly how the inner space of the combustion chamber becomes then filled with jet plumes, while their contact with the walls is markedly reduced.

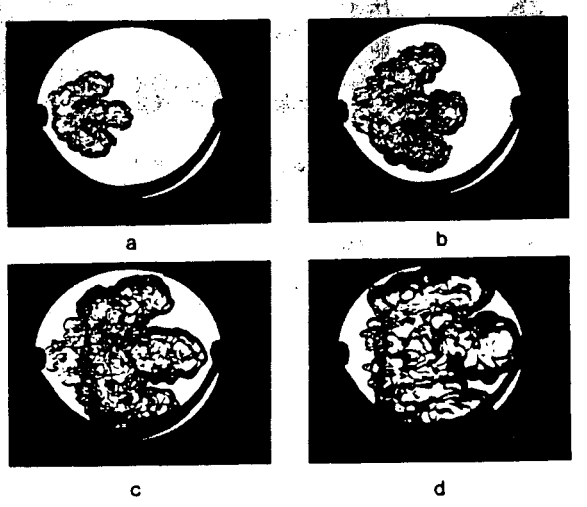

Fig. 10 Schlieren Records of a Triple Orifice PJC System
Orifice diameters: 1.44 mm
Time delay: 20 msec
Times of records denoted by vertical lines in Fig. 9.

Double Generator Systems

The epitome of controlled combustion in engines is a set of sequentially activated PJC generators [19,20]. In approaching such a goal systematically, one has to determine first the performance of two simultaneously activated generators. As to the geometry, the elementary case of opposed jets is the obvious first step. This was then the subject of our subsequent tests.

Displayed in Fig. 11 are the pressure plots obtained with the use of two opposed, single-orifice, PJC generators, in comparison to those of a triple-orifice unit presented in Fig. 9. Shorter rise time, higher amplitude,

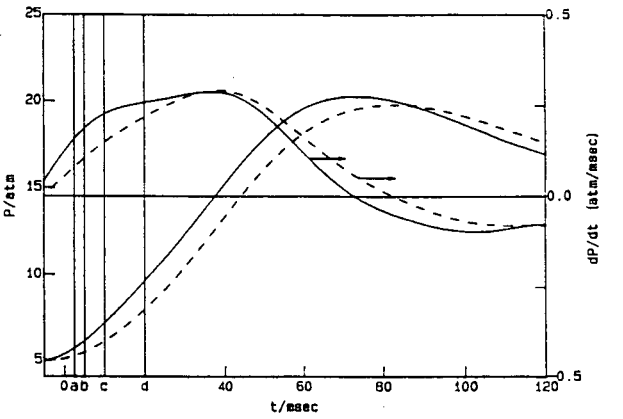

Fig. 11 Pressure Pulse of a Double Generator Single Orifice PJC System
Orifice diameter: 2.5 mm
Time delay: 15 msec.

as well as higher rates of pressure rise, attained with the double generator system in contrast to one, are clearly evident. The corresponding schlieren records are presented in Fig. 12. As expected, the double generator plume fills the chamber more thoroughly than that of a single generator.

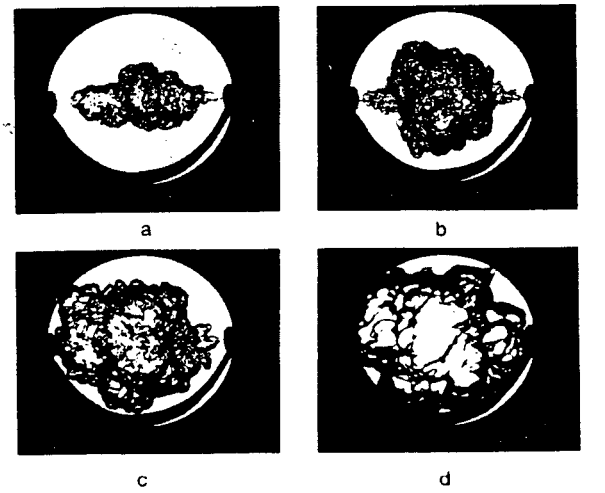

Fig. 12 Schlieren Records of a Double Generator Single Orifice PJC System
Orifice diameter: 2.5 mm
Time delay: 15 msec
Times of records denoted by vertical lines in Fig. 11.

The results of similar tests carried out with triple-orifice generators are presented in Figs. 13 and 14. The pressure plots are shown here in comparison to those of the previous case presented in Fig. 11. Here the higher rate of pressure rise attained with the double generator system is not accompanied by gain in pressure amplitude, a consequence of lesser contact between the burnt gases and the walls occurring with the triple-orifice configuration of a single generator portrayed in Fig. 10.

FTC System

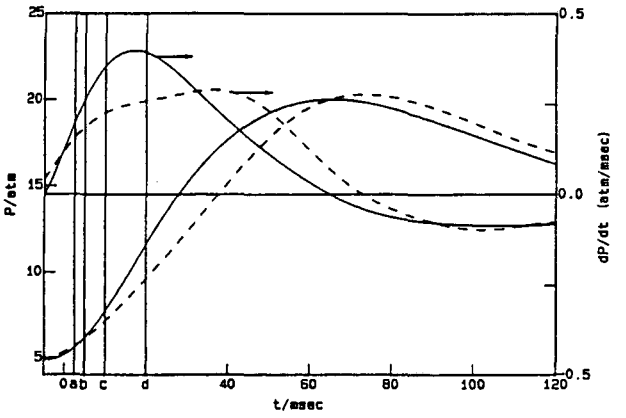

Fig. 13 Pressure Pulse of a Double Generator Triple Orifice PJC System
Orifice diameter: 1.44 mm
Time delay: 15 msec.

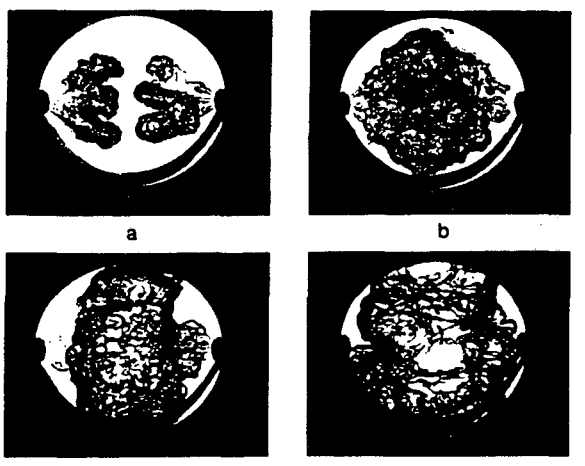

Fig. 14 Schlieren Records of a Double Generator Triple Orifice PJC System
Orifice diameter: 1.44 mm
Time delay: 15 msec
Times of records denoted by vertical lines in Fig. 13.

How about the use of two igniters instead of one in an FTC system? Will this have a similar effect upon the progress of combustion as exhibited by the PJC system? To respond to this question, additional tests were run using conventional spark plugs. The results are displayed in Figs. 15, 16 and 17. We were able to produce a self-sustained flame in the extremely lean mixture of 0.6 equivalence ratio by the addition of a 1 μF capacitor to the ignition system, so that, with 1 kV charging potential, the discharge energy was 0.5 J.

However, as it appears in Fig. 15, the time scale of

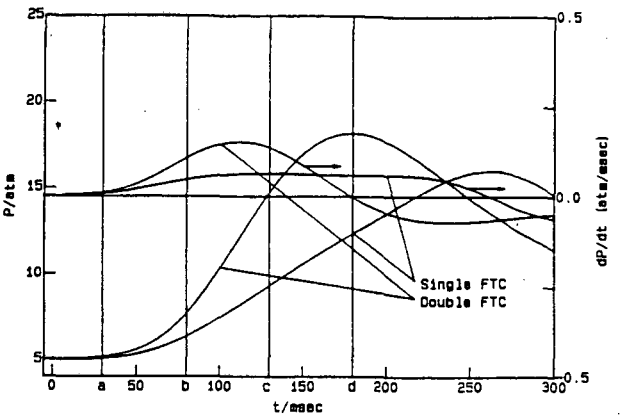

Fig. 15 Pressure Pulses of Single and Double Spark FTC Systems.

the combustion process was then significantly prolonged, similarly as in our previous studies [1]. The flame speed in the extremely poor mixture was, in fact, so low that the effect of buoyancy of the hot burnt gas it enveloped became apparent on the schlieren records of Figs. 16 and 17. Nonetheless, the double flame system exhibited a

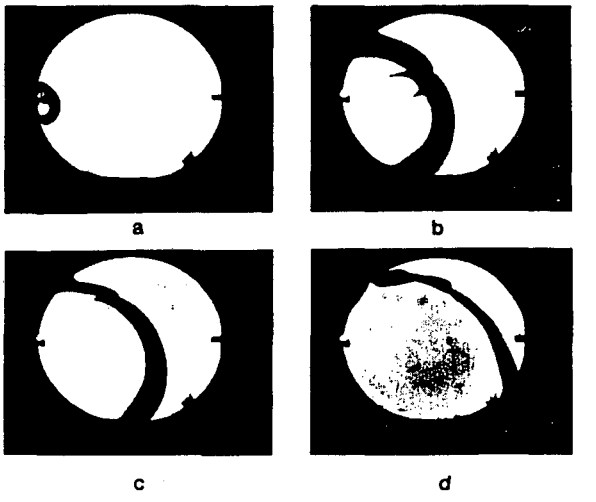

Fig. 16 Schlieren Records of a Single Spark FTC System
Times of records denoted by vertical lines in Fig. 15.

shorter pressure rise time, associated with higher amplitude and rate of rise, than the single flame. According to thermodynamic considerations [18], the attainment of higher maximum pressure is a manifestation of lower total heat loss.

APPRAISAL

In order to assess the merits of our studies, the following facts should be taken into account:

1. As pointed out here at the outset, the concept of

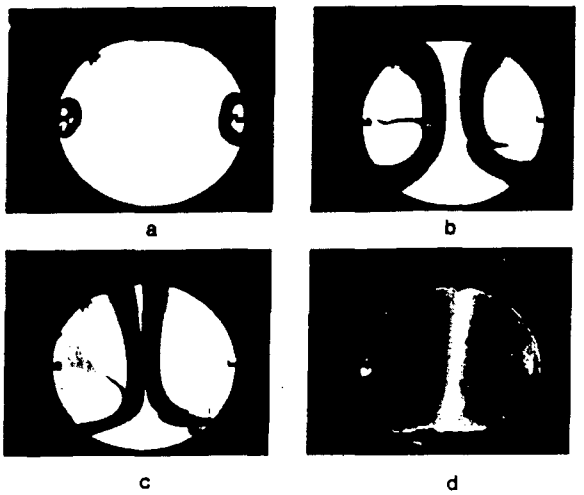

Fig. 17 Schlieren Records of a Double Spark FTC System
Times of records denoted by vertical lines in Fig. 15.

PJC has been studied for decades at the Institute of Chemical Physics, where it was referred to as the LAG process. The advantages of this system have been demonstrated by an extensive program of R&D conducted at the Institute in collaboration with the Gorki Automobile Factory, leading to the development of the LAG engine. The salient feature of the PJC system, demonstrated in this engine as well as in experiments involving turbulent flow fields, is its remarkable ability to initiate and propagate the process of combustion at a relatively high rate in extremely poor mixtures. It is for this reason that it is of particular relevance to the development of what is popularly referred to as a lean-burn engine.

2. Although the LAG process was used solely to develop high compression engines operating on an extremely low octane number fuel, its successor, the PJC system we are studying, offers attractive means for the development of clean and efficient power plants. The reason for it is as follows. The production of NOx is inhibited, while the resistance to knock and the cycle efficiency are enhanced by charge dilution. As a consequence of having the process of combustion executed within the vortex structures of a turbulent mixing zone, rather than at a relatively thin flame front, the residence time of reacting species in the zone of essential chemical activity, the region of high concentration of active radicals, is prolonged, providing the desired time for the oxidation of CO. Vigorous mixing associated with significant entrainment provides optimum conditions to process the charge, promoting thus the elimination of unburned hydrocarbons.

3. The LAG engine, like the CVCC, has been eventually aborted. The essential reason for it has been indubitably the awkward and unwieldy three-valve mechanism and the consequent lack of flexibility, factors leading to disappointingly high pollutant emissions of, especially, unburned hydrocarbons - a universal drawback of all the lean-burn engine systems tested so far. In our opinion, a significant contributing factor was, moreover, the lack of appreciation for the fluid mechanical aspects of turbulent combustion in pulsed jet plumes. It is then the elucidation and amelioration of these aspects that forms the raison d'etre for our work.

4. The primary objective of our investigations is the mechanism of the PJC system. In order to reveal its essential features, all our tests have been performed in a quiescent atmosphere. In a turbulent medium, like that of an engine cylinder, these features are obscured. However, the existence of the essential phenomena under study, namely the multipoint initiation of the exothermic process and the consequent *flameless* or distributed combustion, has been well established under turbulent, lean-burn conditions in engine cylinders, both with the use of a PJC system, exemplified by Gussak and his associates [5-10], and without, as demonstrated by the ATAC engine of Onishi et al. [21] and the TS process of Nogushi et al. [22]. Initial turbulence is, therefore, by no means a hindrance. Moreover, there is a good fundamental reason why residual turbulence in the cylinder cannot have an essential influence upon the function of a PJC system. At the time of ignition in the engine, except for the roll-up vortex which is close to the wall and, hence, out of the way of the active plume, most of the turbulent energy is within the Kolmogorov's inertial range where it decays with the 5/3 power of the wave number. In contrast to that, the turbulent plume is expressed on the energy spectrum in terms of a high amplitude pulse at much smaller wave numbers. There is thus a significant mismatch between the two, impairing their interaction. Finally, in a recently completed independent study, Sayed et al. [23] demonstrated experimentally the superiority of a single stream PJC over the FTC system in a swirl, as well as in a turbulent field. Their conclusions were based primarily on pressure transducer measurements. In the corresponding cinematographic schlieren records, the fluid mechanical features of jet plumes in the latter two cases were, of course, obscured.

5. The engineering dividend of our work is the miniaturization of the pre-chamber, so that it can be accommodated within the body of a conventional 14 mm ignition plug, whereas the third valve is replaced by a small, low voltage, solenoid valve system, activated and controlled by microprocessor signals. As a consequence of the miniaturization of the PJC system, associated with the simplification of its operating mechanism permitting the utilization of a number of individually activated generator plugs, combined with the replacement of the mechanical drive by electronic, a significant amount of flexibility and controllability has been provided for the execution of the exothermic process of combustion in dilute charge engines - a facility that hitherto has not been available. Demonstrated in the paper are some of the ways in which the process of combustion can be thus influenced. Hopefully this will yield the desired technology for the realization of a stratified charge, lean-burn engine system that may eventually satisfy most, if not all, of the expectations we had when this concept was first introduced.

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REFERENCES

1. A. K. Oppenheim, J. Beltramo, D. W. Faris, J. A. Maxson, K. Hom, and H. E. Stewart, "Combustion by Pulsed Jet Plumes - Key to Controlled Combustion Engines," SAE Paper 890153, 10 pp., 1989.
2. J. A. Maxson, and A. K. Oppenheim, "Pulsed Jet Combustion - Key to a Refinement of the Stratified Charge Concept," *Twenty-Third Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, Pa. (in press), 1991.
3. N. N. Semenov, *On Types of Kinetic Curves in Chain Reactions*, Comptes Rendus (Doklady) de l'Academie des Sciences de l'URSS *(I)* 43, 8, 342-348 (1944); *(II)* 44, 2, 62-66 (1944); *(III)* 44, 6, 241-245 (1944).
4. N. N. Semenov, *Some Problems in Chemical Kinetics and Reactivity*. (Transl. by M. Boudart), *1*, 239 pp. Princeton University Press, 1958 ; *2*, 331 pp., Princeton University Press, 1959.
5. L. A. Gussak, "High Chemical Activity of Incomplete Combustion Products and a Method of Prechamber Torch Ignition for Avalanche Activation of Combustion in Internal Combustion Engines," *SAE Trans.*, *84*, 2421-2445 (1976).
6. L. A. Gussak, V. P. Karpov, and D. A. Gussak, "Torch Ignition in a Stratified Charge Engine," *Archiwum Termodynamiki i. Spalania*, *7*, 507-527 (1976).
7. L. A. Gussak, and M. C. Turkish, "LAG-Process of Combustion and Its Application in Automobile Gasoline Engines", IMechE Publication C257/76, *Stratified Charge Engines*, 137-146, The Institution of Mechanical Engineers, London, 1977.
8. L. A. Gussak, "LAG-Process, Some Results of Utilization in Transport and Mechanical Engineering", SAE Paper 789651, *Proceedings of the 13th Intersociety Energy Conversion Engineering Conference*, *3*, pp. 2153-2163, 1978.
9. L. A. Gussak, V. P. Karpov, and Yu. V. Tikhonov, "The Application of LAG-Process in Prechamber Engines", SAE Paper 790692, 26 pp., 1979.
10. L. A. Gussak, "The Role of Chemical Activity and Turbulence Intensity in Prechamber-Torch Organization of Combustion in Stationary Flow of a Fuel-Air Mixture", SAE Paper 830592, 14 pp., 1983.
11. N. N. Semenov, L. A. Gussak, et al., U.S. Patents 3,092,088 (1959), 3,230,939 (1963), 3,283,751 (1966), 3,802,827 (1974).
12. A. S. Sokolik, and V. P. Karpov, "Torch Ignited Combustion - a Novel Mode of Stratification Combustion and Mixing in Diesels", *USSR Academy of Sciences*, *9*, pp. 125-142. 1960.
13. Anon., "Russians go to stratified charge," *Automotive News*, p. 57, April 27, 1981.
14. J. D. Dale and A. K. Oppenheim, "A Rationale for Advances in the Technology of I.C. Engines," SAE Paper 820047, 15 pp., 1982.
15. A. K. Oppenheim, "Quest for Controlled Combustion Engines," SAE Paper 880572, 7 pp., 1988; *SAE Transactions* (in press).
16. A. F. Ghoniem, D. Y. Chen, and A. K. Oppenheim, "Formation and Inflammation of a Turbulent Jet," *AIAA Journal*, *24*, 224-229, 1986.
17. R. Latsch, "The Swirl-Chamber Spark Plug: A Means of Faster, More Uniform Energy Conversion in the Spark-Ignition Engine," [U.S. Patents 4,361,112 (1982), 4,416,228 (1983), 4,465,031 (1984), and 4,509,476 (1985)], SAE Paper 840455, 13 pp., 1984.
18. A. K. Oppenheim and J. A. Maxson, "Thermodynamics of Combustion in an Enclosure," *13th International Colloquium on Dynamics of Explosions and Reactive Systems*, Nagoya, Japan, July 28-August 2, 1991.
19. A. K. Oppenheim, "Method and System for Controlled Combustion Engines," U.S. Patent No. 4,924,828, May 15, 1990.
20. A. K. Oppenheim and H. E. Stewart, "Pulsed Jet Combustion Generator for Premixed Charged Engines," U.S. Patent No. 4,926,818, May 22, 1990.
21. S. Onishi, S. H. Jo., K. Shoda, P. D. Jo., and S. Kato, "Active Thermo-Atmosphere Combustion (ATAC) - A New Combustion Process for Internal Combustion Engines," SAE Paper 790501, 10 pp., 1979.
22. M. Nogushi, Y. Tanaka, T. Tanaka, and Y. Takeuchi, "A Study on Gasoline Engine Combustion by Observation of Intermediate Reactive Products during Combustion," SAE Paper 790840, 13 pp., 1979.
23. I. A. M. Sayed, T. Lezanski, and P. Wolanski, "Performance of a Pulsed Jet Combustion System in a Swirl and in a Turbulent Field," *13th International Colloquium on Dynamics of Explosions and Reactive Systems*, Nagoya, Japan, July 28-August 2, 1991.

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
INFORMATION RESOURCES DEPARTMENT
BERKELEY, CALIFORNIA 94720