

# Control of the Early Combustion by Means of Suitable Ignition

A. Borghese, V. Moccia\* and M. Diana\*

*Istituto Motori, CNR  
Via Marconi 8, 80125 Napoli  
Italy*

*\* University Federico II*

## ABSTRACT

An innovative concept for improving the control of the early combustion in s.i. engines has been investigated. The excitation of small cavities (few mm<sup>3</sup>) by means of a very fast energy release (~100 mJ) is proposed as an effective solution, that provides enhancement of the flame development, resulting from the displacement of the ignition kernel far from the electrodes, and from the intense local mixing between the hot gas pocket and the fresh mixture. Imaged laser shadowgraphy has been applied to describe the ignition of propane/air mixtures in a constant volume reactor. A pulsed laser beam has been used as the ignition source, since it allows to deliver a well-known amount of energy to the ignition kernel in the desired position within the combustion chamber, while retaining all the properties of electrical breakdown sparks. Experimental results are presented showing the superior performance of the proposed solution over wall-located ignition, both in quiescent and turbulent atmospheres. A set of representative behaviors is illustrated, as emerged from parametric investigations carried out on these ignition devices; experimental data are supported by a theoretical model of the cavity depletion, that allows to define the thermo- and fluid-dynamic properties of the outflowing excited gas.

## INTRODUCTION

To date, the matter of ignition in spark ignition engines can be addressed about whether and how many improvements can be achieved, essentially in terms of smaller cycle-to-cycle variations and wider stable operating limits, in order to extend reliable engines' operation to higher EGR or leaner mixtures. Efforts for improving the operating features of conventional coil ignition systems have led to a variety of ideas; among them, the breakdown discharge and the plasma-jet have independently emerged as the most promising means to enhance ignition.

The first systems rely on the fast release of the stored electrical energy in the initial breakdown phase ( $\approx 100$  ns), whereas in the conventional coil ignition systems a

composite spark is produced, consisting in a starting breakdown phase, an arc phase and a glow phase, with decreasing energy-transfer efficiency (1). With a total energy amount of the same order of magnitude ( $\approx 60$  mJ) this high-power, high-efficiency spark shows relevant fluid dynamic effects that interact with the thermal excitation in the sub-millisecond time scale to achieve a faster flame initiation (1-6). These benefits have not been definitely verified in engine or engine-like tests with conventional electrode geometry (7).

The other class of innovative ignition methods is represented by the plasma-jet: the electrical discharge, that typically spans up to the arc phase, takes place in a cavity, forcing a jet of excited gases to enter via an orifice the combustion chamber. The enhancing properties have been identified in the production of chemically active species (H radicals) and in the intense turbulent mixing of excited and cold gases: a wide variety of configurations has been proposed and tested, with geometrical arrangements more or less similar to a sort of prechamber, with or without extra fuel enrichment, but with an energy requirement of about 1 J, an order of magnitude greater than the level of conventional coil systems (6, 8-12). This feature, involving electrode erosion problems, has precluded the practical application of these devices in i.c. engines (6).

The aim of the present work is to propose and describe a new solution to the problem: it relies upon the combined exploitation of a fast spark excitation and a plasma-jet configuration, which is expected to provide additional control of the early combustion phase, combining the benefits and yet overcoming the limitations of the individual approaches.

The characteristics and the feasibility of the proposed solution have been experimentally investigated on a fundamental basis, namely in a constant volume combustion bomb by means of optical diagnostics and pressure recordings, in order to gain the required information in well-controlled conditions; in the meantime, theoretical modeling has been developed to complement the characterization of the system.

## SET-UP AND PROCEDURES

The experiments are carried out in a constant volume cylindrical chamber (diameter 40 mm, height 38 mm), with up to six optical accesses: four 20 mm diameter windows on the side wall and two 40 mm dia. windows on the bases, which allow unimpeded application of optical diagnostic techniques. On the lateral surface there is provision for additional connections of input and output valves and transducers.

The combustion reactor is filled with propane-air mixture with the desired equivalence ratio ( $\phi$ ), prepared injecting the fuel into the transient air flow, during the filling up of the chamber to the working base pressure. After the scavenging phase (input and output valves open), the output valve is closed, starting the charging phase; when the desired pressure is reached the input valve is closed and the system is ready to the combustion phase. The mean entrance gas speed, at the 5 mm diameter input port, can be evaluated from the pressure signal: the level of convective speed has been estimated to be of the same order of magnitude of that present at the end of the compression phase in an s.i. engine, namely tens of meters per second. Accordingly, it has been possible to conduct tests in different fluid dynamic conditions of the charge by simply inserting a given delay  $\tau$  between the valve closure and the ignition start, spanning from maximum field intensity ( $\tau = 0$  ms) to quiescent conditions ( $\tau \geq 1000$  ms). Although the resulting flow field does not present a regular pattern (e.g., as in swirled flow or isotropic turbulence), being produced by a radially entraining jet, and the turbulence levels have not yet been quantitatively evaluated, the method assured top repeatability, allowing to establish well-defined reference conditions for comparison of different ignition schemes.

A personal computer is used to manage the experiments: a first interface board provides software-controlled digital inputs and outputs that allow to drive the electrovalves and injectors, the triggering of the laser, the external digital delay generators and the acquisitions; an A/D interface board is used to collect pressure signals that are sampled at 250 kHz with 12 bit resolution.

Laser shadowgraphy has been used in the present study to visualize combustion from its inception to completion, using a pulsed laser source (Q-switched and doubled Nd-YAG).

The acquisition of shadowgraphs is accomplished by means of a hi-res CCD camera (512×512 pixel, 18 bit) interfaced to another personal computer, entirely assigned to image acquisition, storing and processing.

The software control grants a high level of reproducibility of the experiments: for instance, the accuracy of the equivalence ratio, checked with an Ametek Thermox mod. CMFA-P, was within  $\pm 2\%$ . The time and space resolution of the optical diagnostics, 10 ns and 80  $\mu\text{m}$  respectively, and an accurate timing procedure, allow a global overview of the phenomena on a single-shot basis, with the possibility to explore the phases of interest with the appropriate accuracy.

## METHODOLOGY

In the past years extensive investigations have been conducted about physical and chemical processes induced in quiescent gases by a very fast electrical discharge: the ability of this spark to ignite lean air-propane mixtures was checked and different spatial perturbations were observed, depending on the stoichiometry (2-5).

The characteristics of the electrical spark discharge are basically a very short duration ( $\leq 50$  ns) and an energy release of about 100 mJ. The relevance of fluid dynamic perturbations induced by the impulsive energy release led to investigate the possibility to enhance the ignition process by coupling the chemistry and the gas dynamics. These concepts brought to the realization of the so-called *micro-Plasma-Jet* ( $\mu\text{PJ}$ ): this ignitor, which reflects the features of ordinary plasma-jets, is characterized by a much smaller electrical energy amount and a much faster release, which in turn involve smaller size and shorter residence time in the cavity.

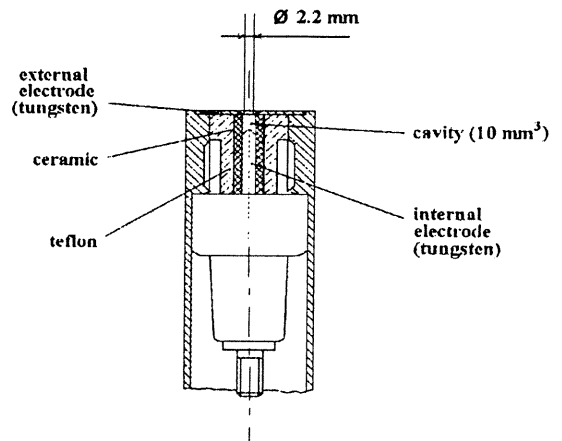


Fig. 1 Constructive drawing of micro-Plasma-Jet

A typical prototype of  $\mu\text{PJ}$  is shown in Fig. 1, consisting in a cylindrical cavity with 3 mm height and 2 mm diameter; the two electrodes coincide with the two bases of the cylinder, one of which is provided with a discharge orifice 2.2 mm diameter; the inner lateral surface is made of ceramic. When  $\mu\text{PJ}$  ignitor is in use, it is positioned on the side wall of the combustion chamber, so that the hot kernel is ejected radially inwards.

In order to thoroughly characterize the proposed solution, it was decided to use as ignition source the optical energy of a Q-switched Nd-YAG laser, working at  $\lambda=1064$  nm, 7 ns duration; this approach has allowed to control the delivered energy, which could be varied from 50 to 250 mJ and precisely measured; in addition, it turned out an easy task to position the ignition kernel anywhere in the combustion chamber, a potentiality that gave way to further investigations. Having focused the attention on breakdown sparks, the laser approach has not to be considered an approximation of any sort, as the properties of the two energy release mechanisms are fully equivalent (2).

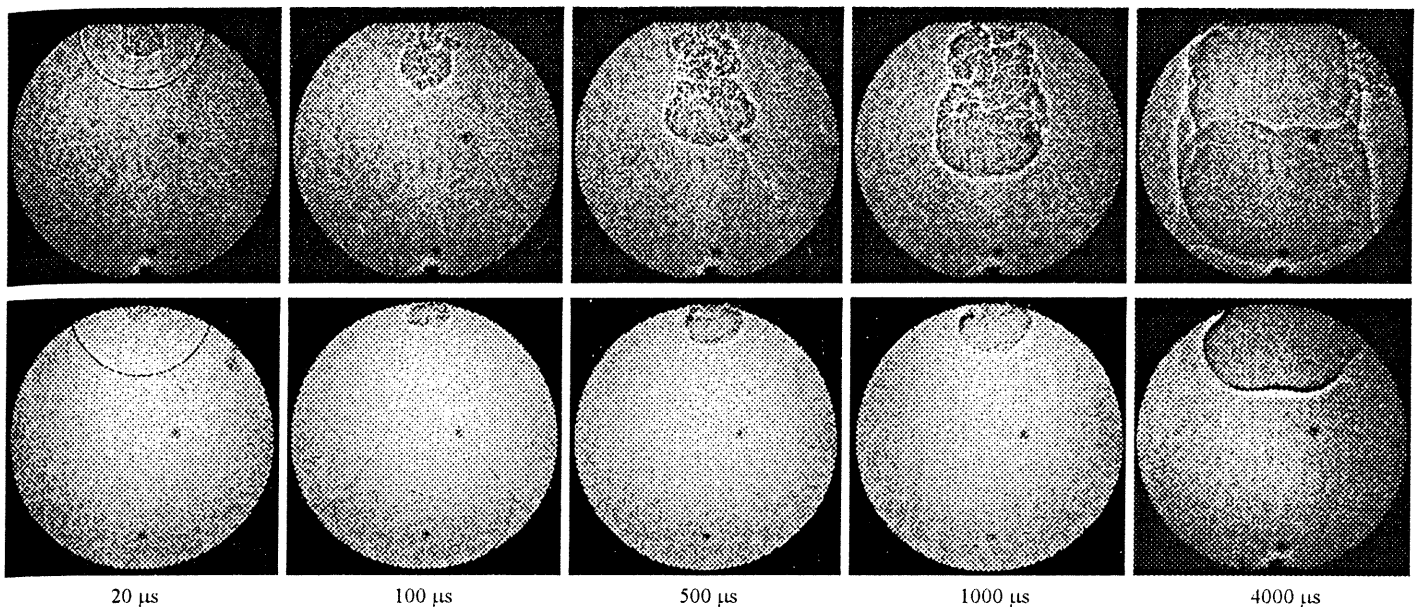


Fig. 2 Shadowgraph data of  $\mu$ PJ (upper) and SI (lower) in quiescent atmosphere

## RESULTS AND DISCUSSION

### a) Analysis of Different Ignition Schemes

All the experiments have been carried out in the described combustion vessel, filled with stoichiometric  $C_3H_8$  - air mixtures ( $\phi = 1.0$ ) at a pressure of 4 bar. The first series of investigations refers to the comparison, in quiescent conditions, of three different geometrical configurations of the ignition kernel: a micro-Plasma-Jet ( $\mu$ PJ), a surface ignition (SI) and a central ignition (CI). These are obtained by focusing the ignition laser beam within the cavity of a  $\mu$ PJ, on the lateral surface of the combustion chamber and in the center of the chamber itself, respectively; the SI case is meant to allow for wall effects, whereas CI reflects their absence, even though both are idealized conditions. The  $\mu$ PJ has a cavity volume of  $10 \text{ mm}^3$  and an orifice diameter of 2.2 mm. The energy level of the laser pulse, measured with a laser Joule-meter, is kept constant at 170 mJ in the three cases.

In Fig. 2 two series of shadowgraphs are reported describing the combustion start and evolution for the  $\mu$ PJ and the SI: these are single-shots taken from different individual events at different time from ignition; nevertheless, due to the reproducibility of the phenomena, their association is allowed to describe typical temporal evolutions.

Different behaviors show up since the first tens of microseconds: in the SI case, after the initial perturbations associated with the impulsive energy release, the combustion kernel grows in a laminar fashion close to the wall; in the case of  $\mu$ PJ, there is a fast protrusion of the excited gases towards the center of the chamber and a blasting growth of the inflamed zone, despite a final laminarization of the flame fronts. These contrasting features are reflected in the corresponding combustion pressures shown in Fig. 3, where the marked superiority of the  $\mu$ PJ over SI is apparent both in the flame development period (time from ignition to 5% of

maximum pressure rise) and in the burn duration (time from 5% to 95% of maximum pressure rise), as defined in (6).

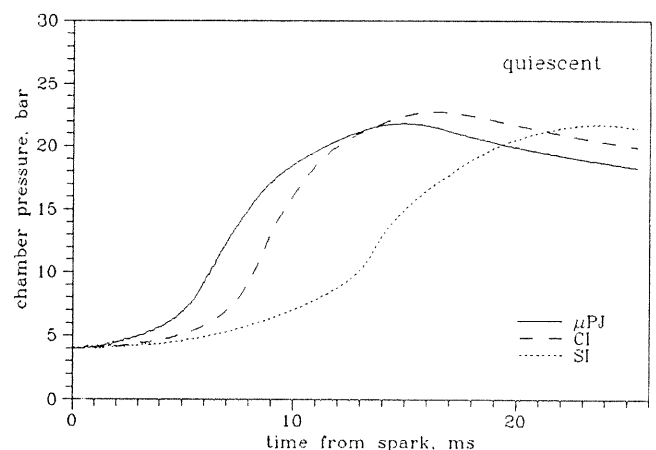


Fig. 3 Combustion pressure of  $\mu$ PJ, SI and CI in quiescent atmosphere

The direct comparison between the conventional spark geometry represented by SI and the cavity-based geometry emphasizes the features of the micro-Plasma-Jet. A more refined characterization rises from the analysis of CI; the pressure signal shows that central ignition exhibits a burn duration similar to the  $\mu$ PJ, but a longer flame development period. Moreover, the enflamed volumes at the same times are smaller and the flame fronts smoother than with  $\mu$ PJ, as observed by shadowgraphic data, not reported here.

From the above considerations the benefits of micro-Plasma-Jet appear in the following terms: the ignition kernel is moved far from the location of the excitation, so that the combustion process evolves avoiding the contact with cold surfaces and minimizing heat losses (13).

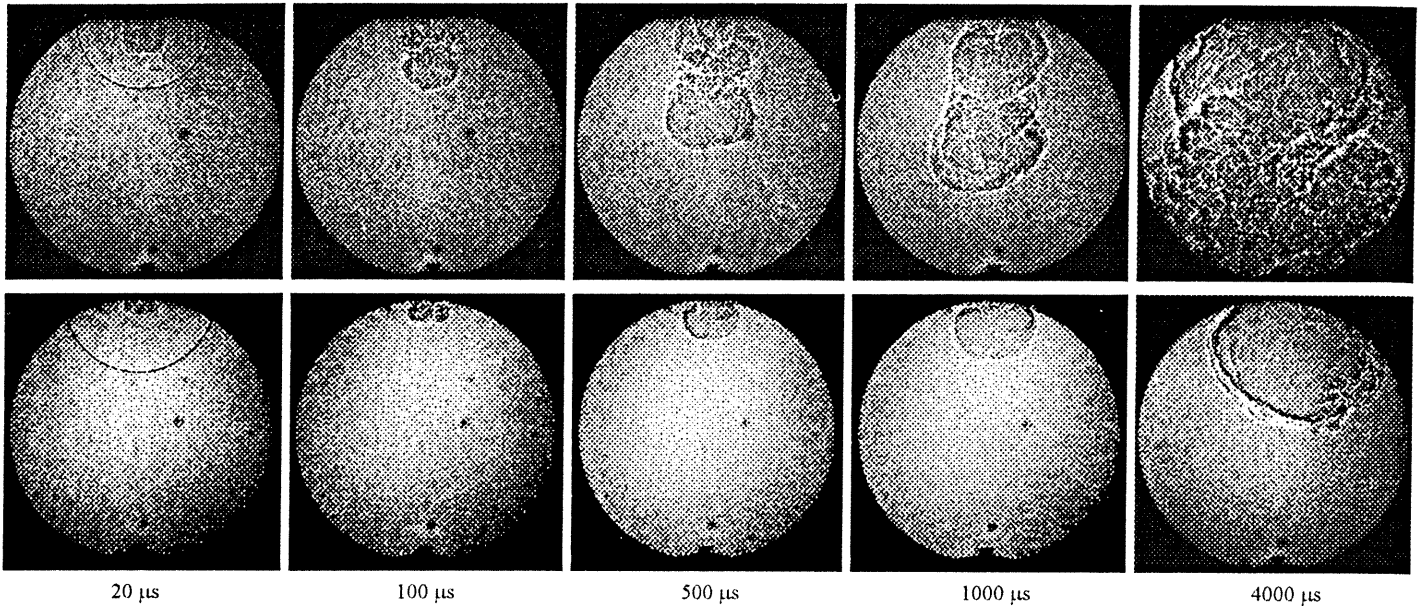


Fig. 4 Shadowgraph data of  $\mu$ PJ (upper) and SI (lower) in turbulent atmosphere

More importantly, the flame surface in the  $\mu$ PJ is larger than in SI, since in the first case the combustion spreads out over the full solid angle, whereas, in the SI case, the presence of the wall limits the flame propagation to a half-space. This implies a higher mass burning rate for  $\mu$ PJ, even assuming a constant burning velocity in both cases. The comparison between  $\mu$ PJ and CI reveals in addition that higher burning rate must be assumed for  $\mu$ PJ, due to the intense fluid-dynamic excitation of the ignition kernel.

nevertheless, even in the case of maximum intensity (ignition delay  $\tau = 0$  ms), clearly discernible effects relate to the different solutions. The  $\mu$ PJ again offers the best performance over the SI and the CI, essentially due to the persisting feature of minimum flame development time. In the growth phase, instead, the pressure recordings of the three cases present a marked similarity, with a nearly coincident slope. The flow field in the chamber has the predictable ability to strongly affect the burn duration, masking long lasting effects, if any, of each ignition system; the differences can be appreciated in the flame initiation phase, which appears to be severely affected not only by the location (see SI vs. CI) but also by the fluid-dynamic state of the ignition kernel (see CI vs.  $\mu$ PJ).

#### b) Micro-Plasma-Jet Operating Features

In order to refine the characterization of the micro-Plasma-Jet, a mathematical model has been developed, which describes the discharging of the cavity following the energy release.

The operating principle of the  $\mu$ PJ can be summarized as follows: the fast excitation of a small gas pocket in a cavity induces a very fast rise of its temperature and pressure; the presence of an orifice allows the displacement at high velocity of the nucleus of excitation in a well-defined direction. Assuming the start of the energy discharge as the time base, a *pre-efflux* phase has been identified, characterized by the plasma relaxation and by an intense mixing: the duration of this phase has been evaluated as the time needed by the shock front detaching from the discharge channel to arrive on the wall of the cavity, and resulted 1  $\mu$ s. At this time the system, assumed to be adiabatic and closed, can be considered well-mixed and homogeneous.

The subsequent dynamics are described assuming unsteady one-dimensional homentropic flow along the axis of the  $\mu$ PJ cavity.

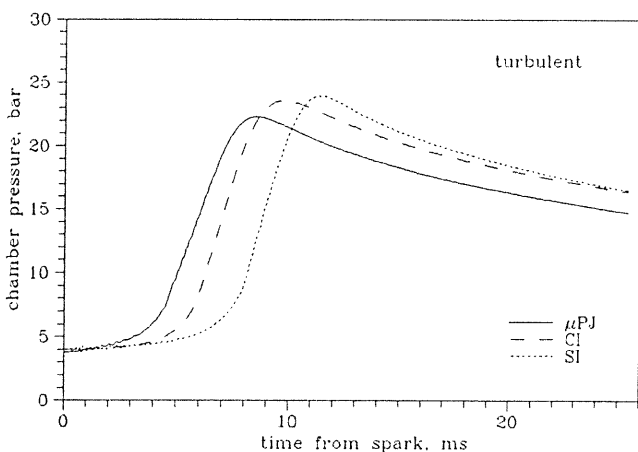


Fig. 5 Combustion pressure of  $\mu$ PJ, SI and CI in turbulent atmosphere

The same ignition schemes have been tested also in turbulent flow field. Figures 4 and 5 show the shadowgraph data and combustion pressures referring to the same operating conditions of the quiescent case ( $\phi=1$ ,  $p=4$  bar,  $E=170$  mJ). As expected, the higher is the field intensity, the shorter are the characteristic times of combustion;

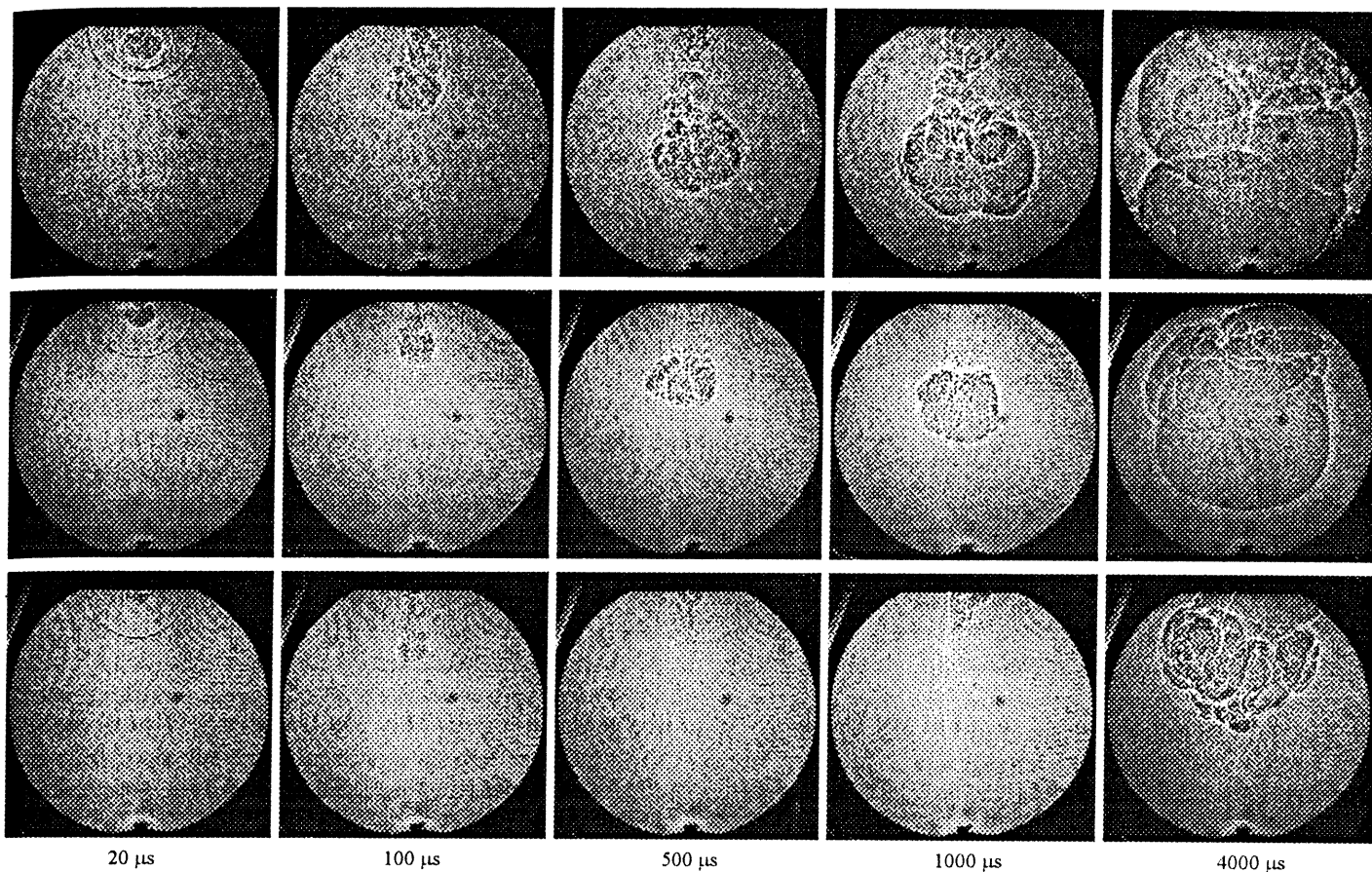


Fig. 6 Shadowgraph data of  $\mu$ PJ #2 (upper), #3 (middle) and #4 (lower) in quiescent atmosphere

In this hypothesis the system is approximated as a cylinder, containing high pressure gas, with a hole on one of the bases, which is suddenly opened to the ambient atmosphere. Equations of continuity, momentum and energy are integrated applying the method of characteristics, with initial conditions estimated as described above and boundary conditions consisting in a closed end and in a partially open end, or nozzle; the gas properties are continuously updated with the local thermodynamic state.

The efflux mechanism is that of quasi-steady one dimensional isentropic flow with constant gas composition; the instantaneous values of the stagnation properties of the flowing gas are evaluated from the static properties in the final section of the cylinder (coincident with the nozzle entrance plane). Approximating the outlet orifice with a converging nozzle, only two possible regimes, sonic and subsonic, are allowed, depending upon the ratio of the internal and external pressure.

The input parameters of the model are the energy release and the geometrical dimensions of the cavity and orifice; the output consists either in  $x$ - $t$  maps of thermodynamic and kinetic properties of the fluid along the cavity at increasing times, or in the time evolution of the same parameters (e.g., pressure, density, temperature, speed) in the restrained section of the orifice.

It should be noted that correlation of this kind of theoretical results with the experimental data is not

immediate: a comparison has been proposed between the critical throat pressure (theoretical) and the pressure behind the shock front (experimental) in the first tens of  $\mu$ s, assuming the equalizing time of the pressure field in the shock volume to be lower than the time of propagation of the shock itself; within the limits of this approach, the correlation showed to be meaningful.

The above-described simulation has purposely been developed to aid interpretation of the unpredictable effects of geometry and energy variations observed in the micro-Plasma-Jet operation: accordingly, a new series of experimental tests has been conducted, backed by theoretical predictions, varying cavity dimensions from 5 to 20  $\text{mm}^3$ , exit hole diameter from 1.5 to 2.5 mm and energy release from 57 to 170 mJ.

Table 1

$\mu$ PJ	#1	#2	#3	#4
energy, mJ	170	170	57	57
volume, $\text{mm}^3$	10	20	5	20
orifice diameter, mm	2.2	2.2	1.5	2.6



In this parametrical analysis at least four different behaviors have been observed: the following three sets of data, together with the previously introduced  $\mu$ PJ case (#1), are to be considered as typical. The other operating conditions remain unchanged for all the cases. In Table 1 the details of the four configurations are summarized.

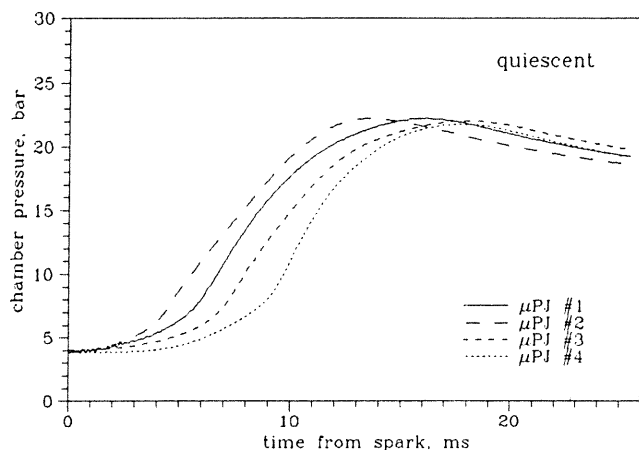


Fig. 7 Combustion pressure of  $\mu$ PJ #1, #2, #3, #4 in quiescent atmosphere

Figure 6 shows shadowgraph exposures for the last three cases. In Fig. 7 the combustion pressure is compared for all the four  $\mu$ PJ configurations.

Theoretical data of interest are summarized in Table 2.

Table 2

$\mu$ PJ	#1	#2	#3	#4
initial mass, $\mu$ g	46	91	23	91
mass ejected in sonic flow, $\mu$ g	41.1	65.1	17.9	40.2
sonic flow duration, $\mu$ s	9.3	12.2	8.5	7.5
mean sonic exit speed, m/s	1008	799	850	542
mean temperature, K	2720	1720	1940	760

In spite of the similar duration of the critical flow phase, the flame development morphologies are rather distinct, as reported by the shadowgraph data, and their effect on a global parameter as the combustion pressure can be easily appreciated.

The best performing cases are #1 and #2: while the former presents higher efflux speed and temperature of the mass ejected, the latter appears to give higher momentum, with a slightly more prolonged sonic phase. The effect in the first case is that of a shorter penetration with an intense energy delivery to the fresh gases, as evidenced by the sharp gradients of the gas between the hot kernel and the exit section; in the other case a greater penetration is obtained

and, even with a less efficient energy exchange, the excited gas volume that will start the combustion results greater.

A down-scaled excitation characterizes case #3, with a lower energy release and a proportionally smaller cavity than in case #2. The percentage of mass expelled in the sonic phase turns out to be slight lower than in case #2, with analogous levels of thermal and kinetic excitation; however the reduction of the absolute quantities that are involved leads to a distinct morphology of the ignition-to-combustion transition: the nucleus of the excited gas appears to travel towards the center of the chamber, without a relevant trace of its path in the gases behind it; in this condition the mixing of hot and fresh gases is drastically reduced, although the ability to displace the kernel remains unaltered.

Case #4 is a typical example of under-excited  $\mu$ PJ, in which the mass ejected in the sonic phase has a thermal and kinetic energy content that is unable to promote combustion: the portion of gases ejected in this phase travels away from the exit orifice, as in the other cases, but the simultaneous mixing with fresh gases has the effect of quenching the flame development. It is noteworthy that the combustion is started by the residual portion ( $\geq 50\%$ ) of hot gas that flows out in the subsonic regime: this positively interacts with the gas that was previously interested by the sonic flow and gives rise to a flame evolution similar to SI, but with a much higher turbulence level.

## CONCLUSIONS

The present work reports on experimental investigations of laser-induced ignition of propane/air mixtures, both in quiescent and turbulent conditions. Laser-ignition, resulting from the optical breakdown of Q-switched laser pulse ( $\sim 10$  ns duration,  $50\div 250$  mJ energy,  $\lambda=1064$  nm), closely reflects that obtained by means of very fast electrical sparks, dealt with in previous works; this approach granted accurate control of the released energy and enabled, in addition, easy and wide variation of some relevant parameters.

Firstly three different boundary conditions of the ignition kernel have been compared: close to the wall (surface ignition), far from the wall (central ignition), and inside a cavity in the wall (micro-Plasma-Jet). Shadowgraph and pressure data show quite distinct behaviors in the three cases: the spatial structure of the ignition kernel, its temporal development and the rate of pressure rise in the chamber allow a clear characterization of the flame growth mechanisms, evidencing the superiority of the  $\mu$ PJ solution.

Further investigations dealt with a parametrical analysis of the  $\mu$ PJ operation, carried out with different cavity volumes, orifice diameters and input energy levels: the variation of these parameters within meaningful limits allows to define the operating range of the micro-Plasma-Jet. Typical behaviors have been identified and reported: i) a fast growth of a turbulent and spheroidal ignition kernel, ii) a streamed ignition due to a high-temperature high-speed kernel, down to iii) a sort of torch-like inflammation. Nevertheless, in all these cases a number of features are

maintained: the times of evacuation of the cavity are of the order of ten microseconds; the percentage of mass expelled in sonic regime is at least of 50 % ; the efflux speed in this phase is of the order of 1000 m/s. Within the limits of the reported results, a  $\mu$ PJ-specific mechanism of ignition has been identified. Ignition enhancement relies on the fast thermal and fluid-dynamic excitation; due to the short time scale, the ignition kernel establishes and grows up in the first millisecond, unaffected by any pre-existing flow field, which, in turn, heavily controls the flame propagation and growth at later stages.

#### ACKNOWLEDGEMENTS

The work has been partly developed within the IDEA EFFECT Project (Contract J0U2-CT92) of the CEC 'JOULE II' Programme.

#### REFERENCES

- Maly, R. and Vogel, M., "Ignition and Propagation of Flame Fronts in Lean  $\text{CH}_4$ -Air Mixtures by the Three Modes of the Ignition Spark", XVII Intern. Symp. on Combustion, The Combustion Institute, pp. 821-831, 1978.
- Borghese, A., D'Alessio, A., Russo, G. and Venitozzi, C., "Time-Resolved Electrical and Spectroscopic Study of Very Short Spark Discharges", Int. Symp. on Diagnostics and Modelling of Combustion in Reciprocating Engines, Tokio, Japan, pp. 77-83, 1985.
- Borghese, A., D'Alessio, A., Diana, M. and Venitozzi, C., "Development of Hot Nitrogen Kernel Produced by a Very Fast Spark Discharge", XXII Intern. Symp. on Combustion", Seattle, pp. 1651-1659, 1988.
- Borghese, A., Diana, M., Moccia, V. and Tamai, R., "Enhancing Ignition by Conditioning the Fast-Spark Induced Flow Field", COMODIA 90, Int. Symp. on Diagnostics and Modelling of Combustion in Reciprocating Engines, Kyoto, Japan, 1990.
- Borghese, A., Diana, M., Moccia, V. and Tamai, R., "Early Growth of Flames, Ignited by Fast Sparks", Combustion Science & Technology, Vol. 76, pp. 219-231, 1991.
- Modien, R.M. and Dale, J.D., "The Effect of Enhanced Ignition Systems on Early Flame Development in Quiescent and Turbulent Conditions", SAE Paper 910564, 1991.
- Pischinger, S. and Heywood, J.B., "A Study of Flame Development and Engine Performance with Breakdown Ignition Systems in a Visualization Engine", SAE Paper 880518, 1988.
- Weinberg, F.J., Oppenheim, A.K. and Teichman, R., "Ignition by Plasma Jet", Nature, Vol. 272, No. 5651, pp. 341-343, 1978.
- Orrin, J.E., Vince, I.M. and Weinberg, F.J., "A Study of Plasma Jet Ignition Mechanisms", XVIII Int. Symp. on Combustion, The Combustion Institute, pp. 1755-1765, 1981.
- Edwards, C.F., Oppenheim, A.K. and Dale, J.D., "A Comparative Study of Plasma Ignition Systems", SAE Paper 830479, 1983.
- Adams, W., Birsztejn, T., Kupe, J.K.Z. and Wilhelmi, H., "Ein neu entwickeltes Plasmastrahl-zündsystem zur Verbrennung von Magergemischen", MTZ Motortechnische Zeitschrift Vol. 49, No. 12, pp. 515-519, 1988.
- Ono, S., Murase, E., Hanada, K. and Fujiki, K., "Combustion Enhancement by Plasma Jet Ignition in Lean Mixtures", JSME International Journal, Series II, Vol. 32, No. 4, 1989.
- Pischinger, S. and Heywood, J.B., "A Model for Flame Kernel Development in a Spark-Ignition Engine", XXIII Int. Symp. on Combustion, pp. 1033-1040, 1990.