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Experimental investigation of the overpressure generated by a low energy plasma igniter☆

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Abstract

This paper presents the experimental investigation of the overpressure created by a low energy plasma igniter. After a short presentation of the plasma igniter design, we rapidly sum the results obtained by employing time resolved spectroscopy. The measurements consist in the determination of the flight time of the overpressure generated by the plasma igniter. Experimental data processing is performed by considering the Sedov–Taylor model.

Keywords: Plasma igniter; Blast wave; Overpressure

1. Introduction

From previous studies on electrothermal launchers (Bourham, Gilligan, Buchanan, & Boyer, 1996), GIAT Industries has developed a micro-torch system (Brevet Giat Industries, 1997), presented in Fig. 1 and especially devoted to plasma ignition. Its scaling and design were made according to similar systems operating with higher energy values.

Its works as follows: a transient electric arc is generated between two electrodes connected to a capacitor bank in a polymer cell in order to produce an ablation of the polymer surface, leading to a highly chemically reactive plasma jet at the exit of the torch nozzle. The transient plasma jet is produced in ambient air.

The micro-torch has an axisymmetric geometry with an axial brass cathode. The micro-torch body is of steel and is used as an anode. The torch nozzle has a diameter of 4 mm and the polymer cell a 2 mm channel diameter. The polymer to be ablated (POM: PolyOxyMethyl-acetal) is a cylinder having the same axis as the micro-torch system. A copper wire (diameter: 0.15 mm) is used to start the electrical discharge. The electrical power supply is a low energy capacitor bank (1.5 kJ) operating at a maximum voltage of 500 V.

2. Electrical discharge and plasma jet characteristics

The plasma duration (about 1 ms) is mainly dominated by the typical times of the electrical discharge and consequently by the capacitor bank design. The maximum current intensity is about 10 kA. The transient plasma jet at the exit of the torch nozzle was first studied by employing time resolved spectroscopy in order to calculate both electronic temperature and elec-

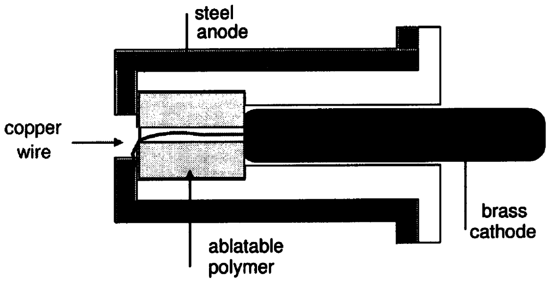

Fig. 1. Schematic drawing of a micro-torch system (cut along the axis).

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tronic density. The experimental procedure and the corresponding results are available in the papers by Caillard (2001) and by Caillard, de Izarra, Brunet, Vallée, and Gillard (2003). Optical spectrum analysis has clearly shown that the plasma was mainly dominated by the presence of neutral copper coming from the explosion of the wire used to initiate the electrical discharge. In addition, the transient electrical discharge produces a strong pressure perturbation which is detailed in the following sections. The velocity of the plasma jet at the exit of the torch nozzle was obtained by measuring the time of flight of an optical perturbation for a known distance with two optical fibers. The value of the ejection velocity depends on the kind of polymer ablated and is between 2500 and 6000 m/s.

3. Set-up for overpressure investigation

Fig. 2 presents the experimental set-up for overpressure investigations (Caillard et al., 2003; Lamy, 1998; Brossard et al., 1984). It includes an horizontal plate with holes at equal distance and on the same axis, where three pressure sensors Kistler 603B are placed. The plasma jet is generated vertically in ambient air, along an axis perpendicular to the axis of the row of pressure sensors. Data sampling is performed simultaneously with a numerical four channel oscilloscope, Lecroy AL 9313.

The piezoelectric pressure sensors have a time response of about 1 ms. Each sensor is connected to a charge amplifier Kistler 5007 trademark and data sampling is triggered by an electrical signal available with the micro-torch power supply (Rogowski coil). Fig. 3 presents a typical set of experimental data obtained simultaneously on the four oscilloscope channels. Channel 3 gives the trigger signal from a Rogowski coil detecting the variation of the current discharge intensity and consequently the beginning of the electrical discharge. Channels 1, 2 and 4 give the instantaneous pressure for the three sensors placed at three different distances from the torch nozzle (these distances are listed in Table 1).

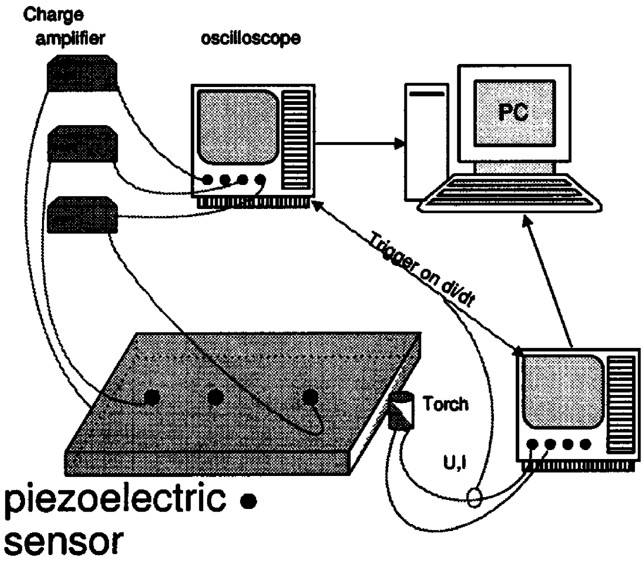

Fig. 2. Set-up for overpressure measurements (Caillard et al., 2003).

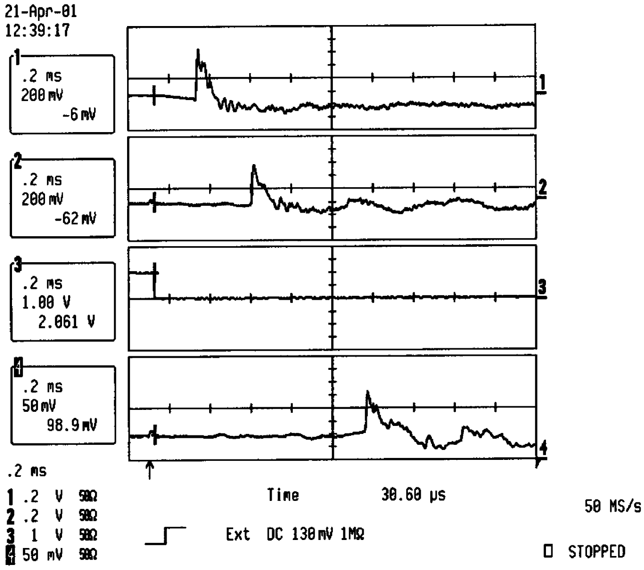

Fig. 3. Typical example of overpressure signals recorded simultaneously by the three pressure sensors (channels 1, 2 and 4). Channel 3 gives the trigger signal.

4. Data processing and results

4.1. Determination of averaged velocity

For each pressure sensor, it is easy to determine the time of flight of the overpressure peak, and then to compute an averaged velocity of the pressure perturbation created by the transient electrical discharge (Table 1).

It appears (see Table 1) that the velocity of the pressure perturbation is systematically higher than that of sound calculated with the temperature and pressure conditions during the experiment ($v_s = 347$ m/s). This

Table 1
Determination of averaged velocity for the pressure perturbation created by the transient electrical discharge

Torch–sensor distance (m)	Time of flight (µs)	Averaged velocity (m/s)
0.07	169	414
0.17	441	385
0.37	998	370

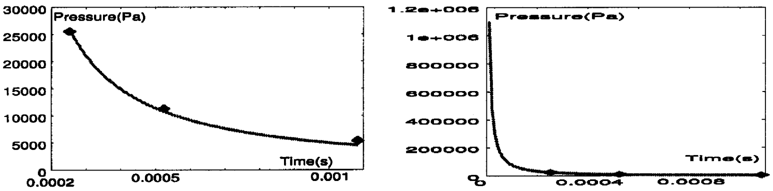

Fig. 4. Plot of the experimental overpressure (points) on the blast wave front as a function of time with two time scales, and the result of the best fitting procedure (continuous line) with the theoretical model given by Eq. (1).

observation, added to the typical shapes of the recorded pressure as a function of time (Fig. 3), shows that the phenomenon of pressure perturbation is a detonation (Lamy, 1998), with blast wave formation.

4.2. Application of the Sedov–Taylor model

Since the experimental conditions of the electrical discharge correspond to the fundamental assumptions of the Sedov–Taylor blast wave model described by de Izarra, Caillard, and Vallée (2002), it was first decided to check that the experimental data are in agreement with the theoretical model.

A first validation can be made with overpressure amplitude p_2 in the blast wave front (overpressure relative to the ambient pressure p_1). The theoretical model of Sedov–Taylor predicts a variation of p_2 as a function of time (Caillard et al., 2003)

$$p_2 = Ct^{-6/5} \tag{1}$$

where C is a constant.

The results of a best fitting procedure with the analytical function (1) are presented in Fig. 4 with two different scales for the time axis; it is obvious that there is a quite good correlation between experimental data and the analytical model (Eq. (1)).

A second validation can be made by considering the time evolution of the blast wave front radius, R. It must be pointed out that the overpressure value p_2 is very close to 0, and consequently, it is necessary to take into account the effect of the ambient pressure in the Sedov–Taylor blast wave model (de Izarra et al., 2002). In this case, the time evolution of R is

$$R(t) = \beta\left(\frac{E}{\rho}\right)^{1/5} t^{2/5} + v_s t \tag{2}$$

where β is a constant depending on the specific heat ratio γ of the gas of specific mass ρ, and E the energy instantaneously deposited and producing the blast wave. For air, β= 1.033. The best fit of experimental data with Eq. (2) gives the following result:

$$R(t) = 0.307t^{0.4} + 352t \tag{3}$$

plotted in Fig. 5. The numerical value obtained (352 m/s) is very close to the speed of sound in air.

We can conclude that the Sedov–Taylor blast wave model is validated, and may be applied to explain the blast wave generated by the transient electrical discharge.

4.3. Determination of the energy E deposited in the blast wave phenomenon

From Eq. (2), it is possible to determine the value of the energy E at the origin of the blast wave. The result of the best fitting procedure (Eq. (3)) gives

$$\beta\left(\frac{E}{\rho}\right)^{1/5} = 0.307.$$

This formula allows the determination of E. We obtain E= 3 mJ. This value appears to be surprisingly low, but one can furnish a physical interpretation. The copper wire used to initiate the electrical discharge has a diameter of 0.15 mm, and a length of 5 mm. The corresponding mass of vaporized copper is about 7.8×10^{-7} kg. In the case when the energy is fully converted into kinetic energy for the mass of vaporized copper, the corresponding speed calculated is about 2700 m/s. This value is very close to the speed of the plasma jet measured at the exit of the torch nozzle with an optical method (Caillard, 2001). Consequently, one can affirm that the energy found by applying the Sedov–Taylor blast wave model corresponds to the

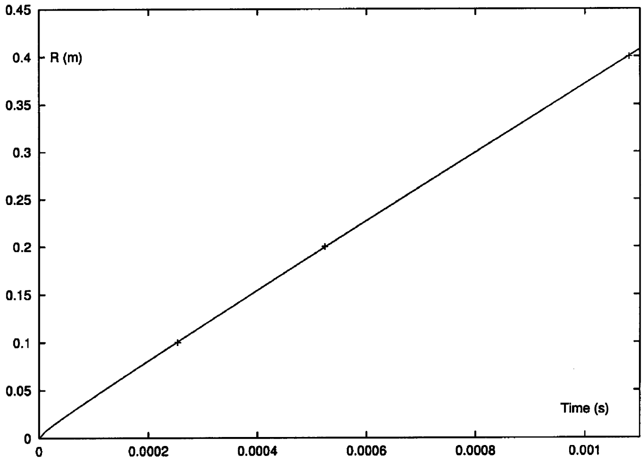

Fig. 5. Plot of the best fitting procedure obtained by applying Eq. (2) to experimental data.

kinetic energy of the vapor copper ejected violently though the torch nozzle at high speed.

5. Conclusion

In this experimental study, we have clearly shown that the transient electrical discharge, employed in the micro-torch plasma igniter, produces a blast wave that could be successfully described by the Sedov–Taylor model. In addition, we have shown that the energy E deposited was very weak, and could be interpreted as the kinetic energy of the exploding copper wire used to start the electrical discharge. At last, the Sedov–Taylor blast wave model may be used to determine the overpressure values at the exit of the torch nozzle.

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