Design and characterization of nozzles and solid propellants for IR laser propulsion

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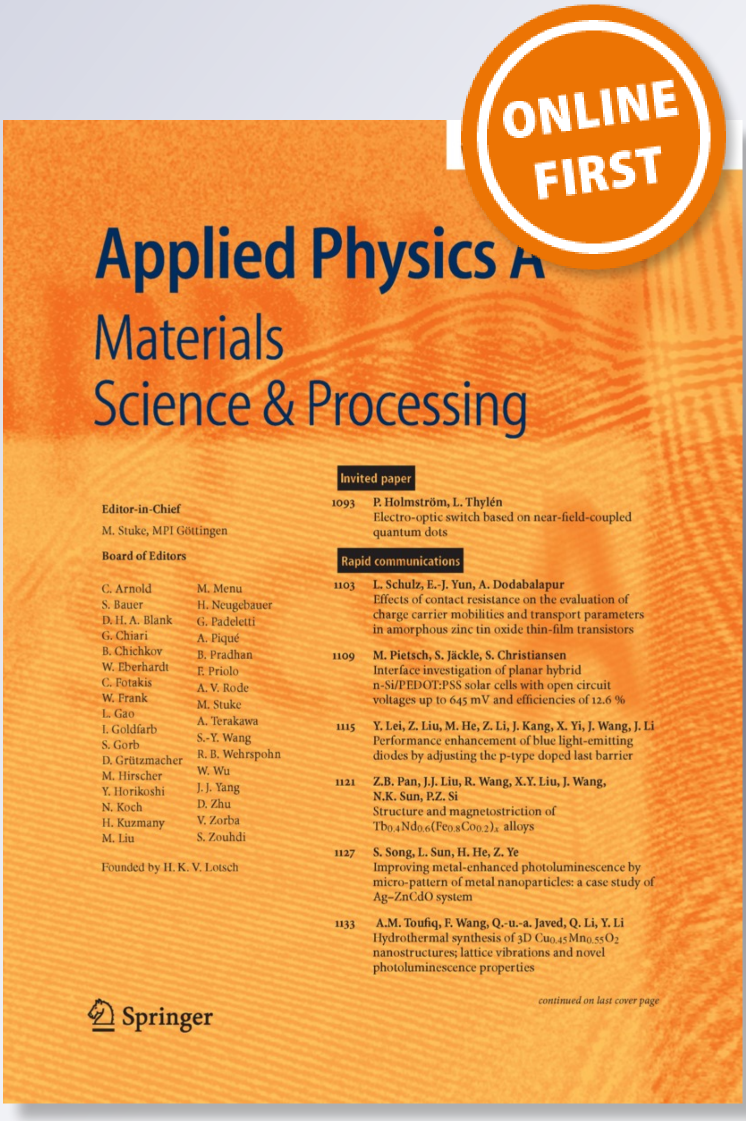
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Design and characterization of nozzles and solid propellants for IR laser propulsion

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Abstract In this article, we present an experimental study of the effect of conical section nozzles coupled to solid targets on laser ablation propulsion. The impulse produced on the target by laser ablation was measured in terms of the coupling coefficient C_m using a piezoelectric (PZT) sensor. The standard deviation of the PZT signal was used as an estimator of the transferred impulse. The ablation was performed with a TEA CO_2 laser at room temperature and atmospheric pressure. The targets were pellets of 90/10 % w/w $Zn/CaCO_3$ concentration ratio. Aluminum nozzles with conical section were coupled to these propellant pellets. A comparative study of the variation of C_m using nozzles of different inlet and outlet diameters of the ejected material as well as of different heights was made. The results demonstrate that for the pellet composition analyzed, as the nozzle's height increases and its diameter decreases improvements up to 250 % respect to the target without nozzle are obtained. These are promising results for the potential development of laser ablation microthrusters.

1 Introduction

Various materials have been investigated and proposed as propellants for laser ablation propulsion [1, 2]. Extensive reviews of laser propulsion propellants and thrusters for space transportation have also been reported [1, 3, 4]. In a previous work, a series of experiments conducted by Rinaldi et al. [5] showed that the intrinsic properties of the binary $Zn/CaCO_3$ propellant favor the thrust generated by laser ablation. Particularly, maximum values of propulsion were reported for $Zn/CaCO_3$ compositions between 70/30 and 90/10 % w/w, respectively. It was also shown that the use of a piezoelectric sensor for measuring the laser ablation impulse of this type of targets is a versatile and simple method which gives equivalent results to those obtained with the usually used torsion pendulum. Later, the same authors have shown that attaching silicon micro-nozzles with square truncated pyramidal shape developed using MEMS technology to the targets, improved the coupling efficiency, C_m [6]. Furthermore, experimental results are reported in which the laser ablation propulsion efficiency improves when using Al nozzles that restrict some specific spatial conditions of the plasmas generated during laser irradiation. Based on empirical results, Li et al. [7] claim that cylindrical nozzles are more efficient than conical. They report that a nozzle to laser beam spot diameter ratio of 2.2–2.4 optimizes the impulse transfer. Another

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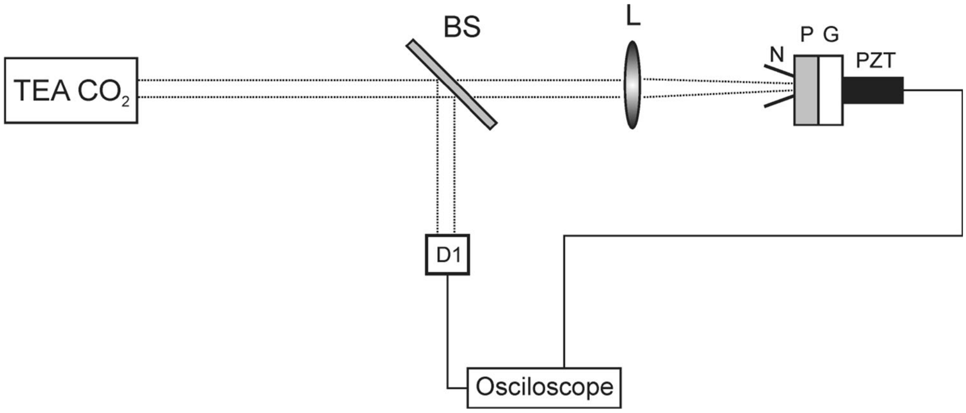

Fig. 1 Experimental setup. *D1* energy meter, *BS* beam splitter, *L* lens, *P* pellet, *G* pellet stand, *N* nozzle, PZT piezoelectric transducer

parameter studied by them was the height of the cylindrical and conical nozzles. In this regard, experimental results indicate that there are two factors affecting the propulsion performance: the length to diameter ratio of the nozzles and the thruster to laser spot diameter ratio.

The aim of this work was to investigate the effect of two parameters of conical section nozzles, the height and the internal diameter, on the laser ablation impulse. In order to do so, the laser emission characteristics were thoroughly controlled. The multimode top-hat profile of the TEA CO$_2$ laser was modified to obtain Gaussian beam emission. In this condition, the output energy was strongly reduced, but the laser spot size and thus the fluence values could be determined with great precision. Solid binary propellants of Zn/CaCO$_3$ mixtures of 90/10 % w/w concentration ratio with and without conical nozzles fixed to the surface were tested. The impulse generated by laser ablation was measured with a piezoelectric sensor. Since the experiments were performed in an irradiation regime in which the C_m value was not optimized, the thrust characteristics improvements obtained from the variation of the different nozzle's parameters were measured in terms of the parameter α, defined as the ratio of the photoacoustic signal with and without nozzle.

2 Experimental setup

The experimental setup is shown in Fig. 1.

Propellant pellet ablation was produced with a homemade pulsed TEA CO$_2$ laser emitting pulses of 60-ns FWHM in the 10.6-μm band. The laser was pulsed at 1 Hz. Single TEM$_{00}$ mode lasing was obtained with an intracavity iris set at 7 mm diameter. The laser output energy was monitored with detector D1 from the beam reflection on a beam splitter. At the pellet plane, the laser energy was 400 mJ and the beam diameter 1.2 ± 0.1 mm. The radiation was focused onto the target with a 9.5 cm focal length ZnSe lens. The laser fluence, 40 J/cm^2, ensured irradiation in the ablation regime [8] and good stability of the photoacoustic signal. The piezoelectric sensor (PZT) used in this work was obtained from a commercial electronic lighter, and the typical physical constants of it are shown in Table 1 (The PZT crystal was not characterized in this work).

Table 1 Typical technical specifications of the PZT sensor

Dielectric constant	$\varepsilon/\varepsilon_0$	4.5
Coupling factor	K33	0,09
Charge constant	D33 10^{-12} C/N	2
Voltage constant	G33 10^{-3} Vm/N	−50
Quality factor	Q	10^4–10^6
Frequency constant	Fr	32 kHz

The ablation process is governed and characterized by the matrix composition. Zn was selected as ablation matrix since it favors the ablation process due to its physical and thermal properties: low ionization potential and high electronic density [9, 10]. There is also experimental evidence that a small amount of salt (CaCO$_3$) can produce large effects on the process of emission of light and particles during the ablation of a Zn matrix [9]. In view of the results obtained in a previous work [6], pellets with 90/10 % w/w Zn/CaCO$_3$ composition were prepared. Zn metal powder (Mallinckrodt, 99.90 %) and CaCO$_3$ powder (Aldrich powder, 99.99 %) were mixed in a mortar. They were subsequently powdered using a mill and then pressed in two stages. In the first stage, a pressure of 36 kpsi was applied for 10 min, and in a second stage, the pellets were additionally pressed with 54 kpsi during 5 min. This pressure reduces strongly the effects of the size of the particle in the ablation process, increasing the homogeneity of the surface of the sample and reducing its humidity content. Pellets 1.0 cm diameter and 3.4 mm thick with masses between 730 and 750 mg were obtained. The impulse transmitted to the samples was measured with a piezoelectric transducer [6].

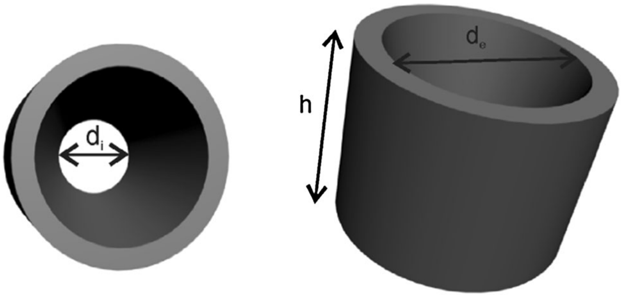

Fig. 2 Nozzle's scheme. d_i internal diameter, d_e external diameter, h height

The geometry of the nozzles was conical. In Fig. 2, a schematic view of the nozzles is shown. The geometrical parameters varied were the height, h, the internal diameter, d_i, and the external diameter, d_e. The height of the nozzles was varied between 3.0 and 5.0 mm. The internal diameter was between 2.0 and 4.0 mm and the external diameter was approximately 5.0 mm for all the nozzles.

The pellets were mounted on a xyz optical translation unit allowing displacements with micrometric resolution. In order to ensure reproducibility of the experiments with different pellets, a cylindrical glass with the same radius of the pellets was stuck to the surface of the piezoelectric. In each experiment, the pellets were pasted to the surface of this glass with silicone grease.

PZT signals were acquired with and without nozzles. A magnifying glass allowed to control that the laser impinged both on the center of the pellet and on the center of the nozzle. The effect of the nozzle was estimated from the ratio of the standard deviation of the photoacoustic signals with and without nozzle (PZT_n) and (PZT_{wn}), respectively. The coupling coefficients were obtained from these photoacoustic signals.

3 Results and discussion

As it was shown in a previous work [9], a small amount of salt in a metallic matrix produces an increase in the processes of light and particles emission due to the high value of the enthalpy of vaporization of the added salt. The same effect is manifested in the design of a polymer with optimum propellant properties, since it requires a very low thermal conductivity and a high enthalpy of decomposition to ensure the maximum thrust [1]. Taking into account the effect of added salt on metals and applying the design parameters based on the work of Phipps et al. [1] for the polymer propulsion processes, the solid propellants based on a matrix of metallic zinc with calcium carbonate were developed.

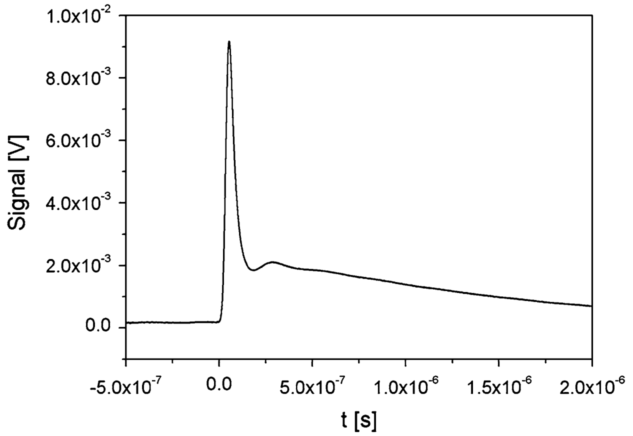

Fig. 3 Time profile of the laser pulse

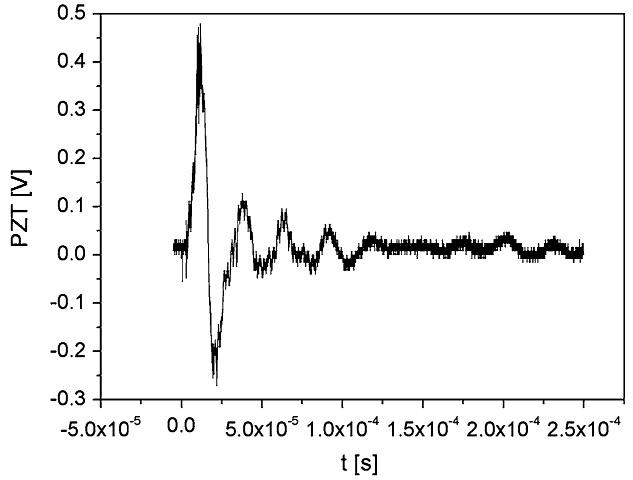

Fig. 4 Typical time dependence of the piezoelectric transducer signal

In the laser ablation processes, particularly in metals [11], when the laser fluence attains the vaporization energy, the metal is ejected from the surface. This low-energy absorption process inhibits the energy transfer to the impulse, and thus, a low coupling coefficient, Cm, is obtained. On the other hand, if the laser fluence is increased to obtain a larger Cm value, the energy is consumed in thermal and chemical processes that do not contribute to the expected enhancement. In the case of the inorganic oxides or salts, the vaporization energy is very high [10]. High fluence values are required to eject the material from the surface but, when the phenomenon occurs, large Cm values are obtained. The main problem with these oxides or salts is their fragility. They cannot be directly irradiated since they crack after the first laser pulses. For this reason, they cannot be used as propellants. In the particular case of Zn, its combination with oxides or salts produces a matrix that behaves as an oxide or salt inhibiting the vaporization

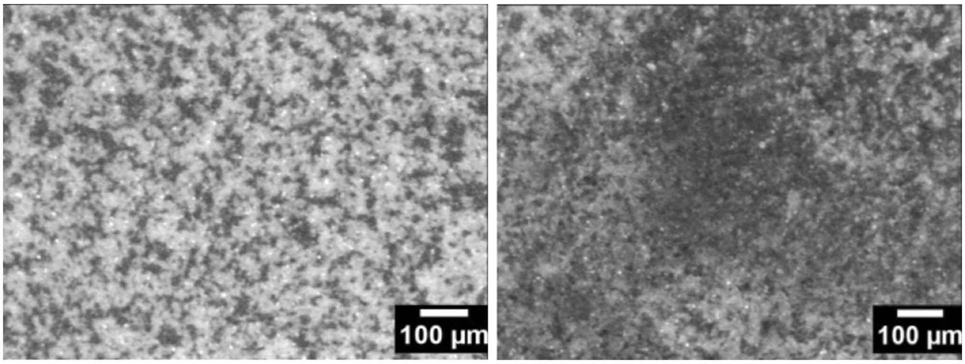

Fig. 5 The *left* and *right* images correspond to the surface of the pellet *before* and *after* irradiation, respectively

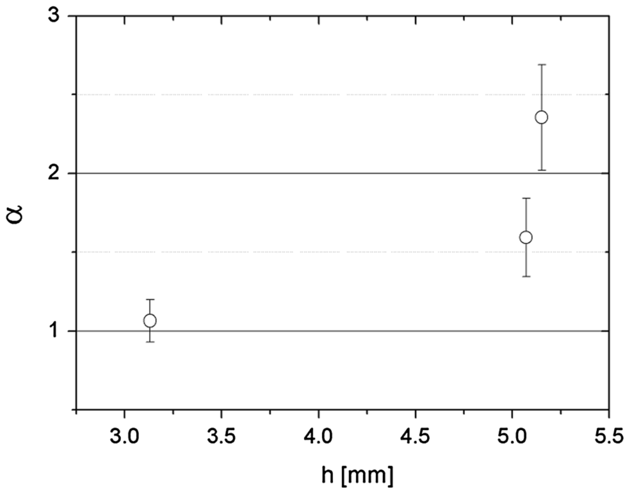

Fig. 6 α dependence on the height of the nozzles

at low fluences and at high fluences absorbs a large amount of energy and converts it into impulse, thus increasing the Cm value. Other metals such as aluminum were not tried because as stated in the literature [9] when combined with oxides or salts the resulting matrix usually crumbles when irradiated by the laser.

Relevant parameters for the process are the laser spot size and the pulse duration. Figure 3 shows a typical time profile of the average of 100 laser pulses detected with a photon drag detector. As can be observed, it consists of a 60-ns FWHM needle followed by a ≈2-μs tail. This gives an energy density of 630 MW cm^{-2}.

Figure 4 shows a typical time profile of the acoustic signal registered with the piezoelectric transducer. It can be observed that the time period associated with these phenomena is an order of magnitude higher than the laser pulse length.

Figure 5 shows an image of the surface of one of the pellets before and after irradiation obtained by optical microscopy. The light areas correspond to $CaCO_3$ and ZnO while the dark ones to Zn. The white areas are reduced after irradiation due to ablation of $CaCO_3$ and ZnO while the dark ones are increased due to the enrichment of Zn.

The coupling coefficient was estimated from Eq. (1) where Δp is the impulse imparted to the pellet and E the laser energy.

$$C_m = \frac{\Delta p}{E} \tag{1}$$

The SD of the PZT signal was used as an estimator of the impulse transmitted to the pellet [5, 6]. This estimator was chosen since it is quite independent of the different oscillation modes of the pellet–PZT system.

The same calibration of a previous work [5] was used for the determination of the transmitted impulse and the coupling coefficients. As an estimator of the nozzles' efficiency, the $\mathrm{PZT_n}$ to $\mathrm{PZT_{wn}}$ ratio, α, was determined. $\mathrm{PZT_n}$ and $\mathrm{PZT_{wn}}$ were obtained as the mean values from 10 signals and the uncertainties from the respective standard deviations.

Figure 6 shows the $\mathrm{PZT_n}$ to $\mathrm{PZT_{wn}}$ ratio dependence on the height of the nozzles. Figure 7 shows the $\mathrm{PZT_n}$ to $\mathrm{PZT_{wn}}$ ratio dependence on the internal diameter of the nozzles. Table 2 summarizes the results obtained.

The PZT signal increased with increasing height and with decreasing diameter of the nozzles. The optimum condition was obtained for a height of approximately 5.0 mm and an internal diameter of approximately 2.0 mm. In this condition, the magnification of the photoacoustic signal was about 250 %. If the internal diameter of the nozzle is much larger than the ablated area, an α value of approximately unity is expected. On the other hand, if the internal diameter is smaller than the ablated area without nozzle, the α value will be strongly reduced. Thus, as the internal diameter is varied between these two limiting values, an optimum value of α will be obtained. This optimum value will depend on the laser energy, the laser spot size and the ablation threshold of the irradiated material. In a previous work [12] in which a shadowgraph study of the acoustic wavefront progress after ablation was performed, an increase of the transferred impulse with increasing nozzle's height was observed as a consequence of the enhancement of the mass flow at the exit of the nozzle. This result is in good agreement with those of this work.

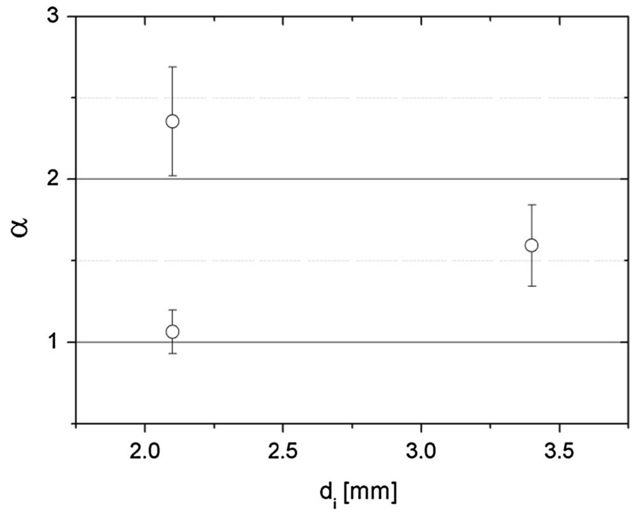

Fig. 7 α dependence on the internal diameter of the nozzles

Table 2 α and C_m values for the different nozzles used

d_i (mm)	h (mm)	α	C_m
2.1	3.13	1.1 ± 0.1	1.4 ± 0.1
2.1	5.15	2.4 ± 0.3	3.0 ± 0.2
3.4	5.07	1.6 ± 0.2	2.1 ± 0.2

d_i internal diameter, h height

At present, numerical studies of the changes introduced by the nozzles on the plasma generated by the laser in the area surrounding the focal region have been undertaken [13]. The aim of these studies was to investigate whether these changes are representative of those introduced by the ablated material. Since the experiments are most time consuming mainly because each pellet is used only once, the simulation would allow to study the effects of the internal diameter and the height of the nozzle and to determine the geometry that optimizes the propulsion. Also by adjusting the initial conditions of the velocity field, the temperature and the pressure of the plasma, we will be able to infer results regarding the laser's spot size and the ablated area, which depends on the damage threshold of the metal/salt composition.

4 Conclusions

An experimental study of the performance of conical nozzles on laser ablation propulsion was performed. An increase of the photoacoustic signal is obtained increasing the height or reducing the diameter of the nozzle. The maximum optimization obtained for a laser energy of 400 mJ and a spot diameter of 1.2 mm was about 250 % with a nozzle of 5.0 mm high with an internal diameter of 2.0 mm. The results of this work are very promising for the potential development of laser ablation microthrusters.

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