Experimental Investigation of the DEAS Concept in Hypersonic Flow

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Abstract. *The present paper presents the experimental results on the Laser-Supported Directed Energy "Air Spike" – DEAS in hypersonic flow achieved by the Laboratory of Aerothermodynamics and Hypersonics – LAH, Brazil. Two CO_2 TEA lasers, sharing the same optical cavity, have been used in conjunction with the IEAv 0.3m Hypersonic Shock Tunnel - HST to demonstrate the Laser-Supported DEAS concept. Single and double laser pulses, generated during the tunnel useful test time, are focused through a NaCl lens upstream of a Double Apollo Disc model fitted with seven piezoelectric pressure transducers. Surface pressure distribution and the photographs of the hypersonic flow over the model are presented.*

Keywords: *Directed-Energy Air Spike, Drag reduction, Hypersonic Shock Tunnel, Experimental Hypersonic Flow*

1. INTRODUCTION

It has been suggested by several authors (Myrabo, 1978; Tidman, 1990; Myrabo and Raizer, 1994; Gurijanov and Harsha, 1996 and Covault 1999) that aerodynamic drag and heating of a hypersonic Trans-Atmospheric Vehicle, TAV, could be greatly reduced by adding energy to the air ahead of it. Myrabo and Raizer (1994) have suggested focused a powerful laser (or microwave) beam ahead of the TAV flight path and it has been demonstrated by Minucci et al. (2000 to 2003). Myrabo and Raizer (1994) called the effect of reducing aerodynamic drag and heating through the use of electromagnetic radiation) laser energy addition) by Directed Energy Air Spike, DEAS, effect. A laser driven TAV, resembling two Apollo re-entry heat shields mounted back to back, was even suggested by Myrabo. The experimental TAV, which makes use of the Laser-Supported DEAS effect, is depicted in Fig. 1. In this situation, the DEAS in front of a vehicle is created by a shock wave propagating from a Laser-Supported Detonation, LSD, wave, Fig. 2. The pressure at the wave front, being higher than atmospheric pressure, deflects the incident hypersonic airflow from the axial direction and forces it to flow over the air-spike to the periphery of the vehicle, Fig. 1.

Fig. 1. Conceptual Lightcraft TAV using the DEAS effect.

The baseline of the present paper is to provide better scientific experiments to corroborate Myrabo and Raizer (1994) DEAS concept for a new propulsion system, Fig. 1. A propulsion system design of a transatmospheric vehicle using a DEAS inlet presents two important advantages: 1) it employs a detached parabolic-shaped shock wave, Fig. 2, to contain a rarefied "hot air pocket" which substantially reduces the flow Mach number impacting the vehicle forebody, thus decreasing the aerodynamic drag, and, most importantly, 2) it deflects the oncoming hypersonic air flow from the vehicle's path into an annular hypersonic inlet at the periphery of the vehicle where a MagnetoHydroDynamic, MHD, engine could be located. The inlet air can either be subsequently accelerated by an MHD slipstream accelerator to produce thrust, or decelerated to extract onboard electric power.

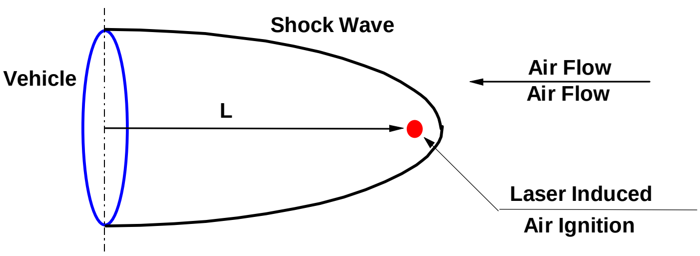

Fig. 2. Schematic of the DEAS concept.

The present paper presents experimental results on the Laser-Supported *Directed Energy "Air Spike" – DEAS* (by focusing a laser beam ahead of the model) in hypersonic flow achieved by the

Laboratory of Aerothermodynamics and Hypersonics – LAH, Brazil. Two CO_2 TEA lasers, sharing the same optical cavity, have been used in conjunction with the IEAv 0.3m Hypersonic Shock Tunnel - HST to demonstrate the Laser-Supported DEAS concept.

2. EXPERIMENTAL APPARATUS

The IEAv 0.3-m. Hypersonic Shock Tunnel, Fig. 3, was used to produce high to low enthalpy hypersonic flow conditions (Nascimento and Minucci, 1997). In the high enthalpy runs, helium was used as the driver gas and the tunnel was operated in the equilibrium interface condition to produce a useful test time of roughly 500μs and reservoir conditions of 5,000 K, temperature, and 120 bar, pressure. In the low enthalpy case, air was used as the driver gas to produce a useful test time of 1.5 ms and reservoir conditions of 950 K, temperature, and 25 bar, pressure. The test section airflow Mach number was 6.2 in the high enthalpy tests and 7.8 in the low enthalpy ones. The same conical, 15^o half angle, 300mm exit diameter, nozzle with a throat diameter of 22.5mm was used in all cases. The different Mach numbers achieved are the result of the different reservoir conditions and real gas effects present in the tests.

Fig. 3. IEAv Hypersonic Shock Tunnel test section and the CO_2 TEA laser heads.

A single and a multi laser pulse generated during the tunnel useful test time were focused through a NaCl lens ahead of a *Double Apollo Disc model* (very similar to the Fig. 1) fitted with seven piezoelectric pressure transducers. One of the tunnel test section access windows had to be modified to accommodate the laser beam delivery system. This system consisted of a 50mm diameter NaCl lens with a focal distance of 180 mm mounted in a telescope. The telescope is free to move inside a support mounted to the test section window so that the focus can be adjusted to be in the nozzle centerline. Once positioned, the telescope is locked in position so that it does not move during the test. Due to geometrical constraints the telescope had to be installed 45^o with respect to the nozzle centerline. This causes the lens to be damaged frequently and, sometimes, destroyed by high-speed particles/debris that reach the test section. In addition to that, due to the fact the air plasma, created in the focal point, tends to propagate towards the laser source the energy addition region is not symmetrical with respect to the nozzle centerline.

Two Transversely Excited Atmospheric pressure, TEA, Carbon Dioxide Lasers, designed and built by Watanuki et al (1988), are used to drive the DEAS. The two lasers share the same optical cavity. Figure 3 shows the laser heads, the beam delivery system and the hypersonic shock tunnel test section. Each one of the lasers, in multimode operation, is capable of producing a single high energy, 4.5 J, short pulse, 120 ns (FWHM), at 10.6 μm, Table 2. The output beam has a rectangular cross section, 34mm X 17mm.

Table 1 Shock-tunnel test conditions.

PARAMETER	MEDIUM ENTHALPY
Reservoir pressure, bar	173.0
Reservoir temperature, K	1685.0
Reservoir enthalpy, MJ/kg	1.9
Freestream Pressure, mbar	23.2
Freestream temperature, K	158.4
Freestream density, g/m^3	51.1
Freestream Mach number	7.3
Useful Test Time, millisecond	1.0

Table 1 presents the nominal shock tunnel test conditions. These conditions did not vary more than 5% from run to run. The laser operating conditions can be found in Table 2.

Table 2 CO_2 TEA lasers operating conditions

	SINGLE PULSE	MULTI PULSE	
Energy per pulse (Joules)*	TEA #1	TEA #1	TEA#2
	7.5	4.5	4.5
Pulse Duration (ns)	120	120	
Gas Mixture	7%CO_2-54%N_2-39%He	14%CO_2-14%N_2-72%He	

***Average between the energy meter readings immediately before and after the test**

The two laser pulses, 50 μs apart, were synchronized with the shock tunnel useful test time via a time delay generator triggered from a piezoelectric pressure transducer, located immediately upstream the nozzle entrance. Three photodiodes were used as light sensors to monitor the generation of the laser pulse inside one of the laser head (sensor # 3), the production of the laser induced air ignition inside the test section (sensors # 1 & 2) and the natural air luminosity of the hypersonic/hypervelocity flow around the model (sensor # 2). Two additional piezoelectric pressure transducers, 0.5 m apart, located in the tunnel driven section, were used to time the incident shock wave.

A single and a multi laser pulse experiments, time-lapse type photographs of the luminous air flow around the model and of the laser-induced air ignition were taken by using a Nikon camera model N6006 with AF35-70mm f/3.3-f/4.5 Nikkor lenses and ISO 100 color film.

All the data, with the exception of the flow visualization, were recorded using a Tektronix VX4244 16-channel 200kHz data acquisition system.

In the experiments, a Double Apollo disc, wherein the upper and lower contours are identical and are based on the Apollo command module's lower heat shield. The 100mm diameter model houses pressure transducers as showed in Fig. 4, and it is positioned 100mm downstream of the air ignition.

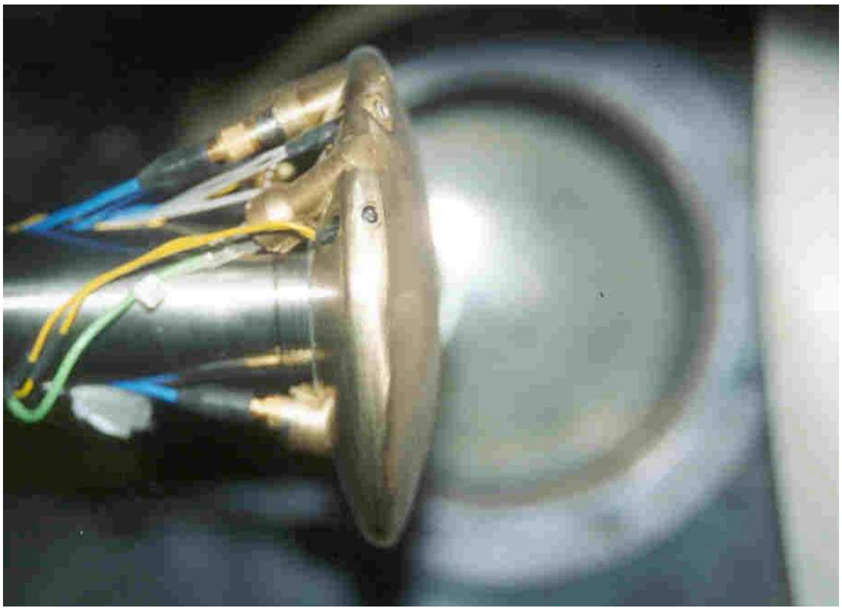

Fig. 4 Photograph of the instrumented Double Apollo Disc model.

3. RESULTS AND DISCUSSION

Single Laser Pulse Results

For the medium enthalpy conditions present in Table 1, and the conditions show in Table 2, the Double Apollo Disc model, Fig. 4, was tested. Surface pressure measurements can be found in Fig. 5. Such pressure measurements are non-dimensionalized by the impact pressure and the radial position of the pressure taps, r, by the model radius, R. As one can see, the surface pressure level over most of model front surface for DEAS-off is much higher than that given by DEAS-on. As a consequence, the laser-supported DEAS was able to generate a decrease in the surface pressure distribution over the model tested. This result is in agreement to that obtained with the simple hemisphere-cylinder model carried out by the authors (Minucci et al., 2000-2003). On the other hand, a pressure increase was detected near the model periphery.

Figure 6 shows a time-lapse photograph of the laser-induced air breakdown upstream of the model at Mach 7.3 flow conditions, Table 1. Due to stray light it is possible to see internal details of the test section, the sting mount, the nozzle exit and even the infrared telescope mounting behind the sting. Since it is a time-lapse photograph, every luminous phenomenon that took place inside the test section was recorded onto the photographic film. Therefore, it is also possible to observe in Fig. 6 both the bow shock in front of the model and the conical flow structure upstream of it.

The conical flow structure seen in Fig. 6 seems to agree with the DEAS mechanism proposed by Myrabo and Raizer. As soon as the laser-induced air breakdown develops, the air is pushed by the LSD wave from the region immediately upstream of the model, and over the "Air Spike" to the periphery of the hemisphere generating the conical flow structure seen in Fig. 6. This conical flow structure creates a detached conical shock wave (parabolic-shaped) well ahead of Double Apollo Disc model.

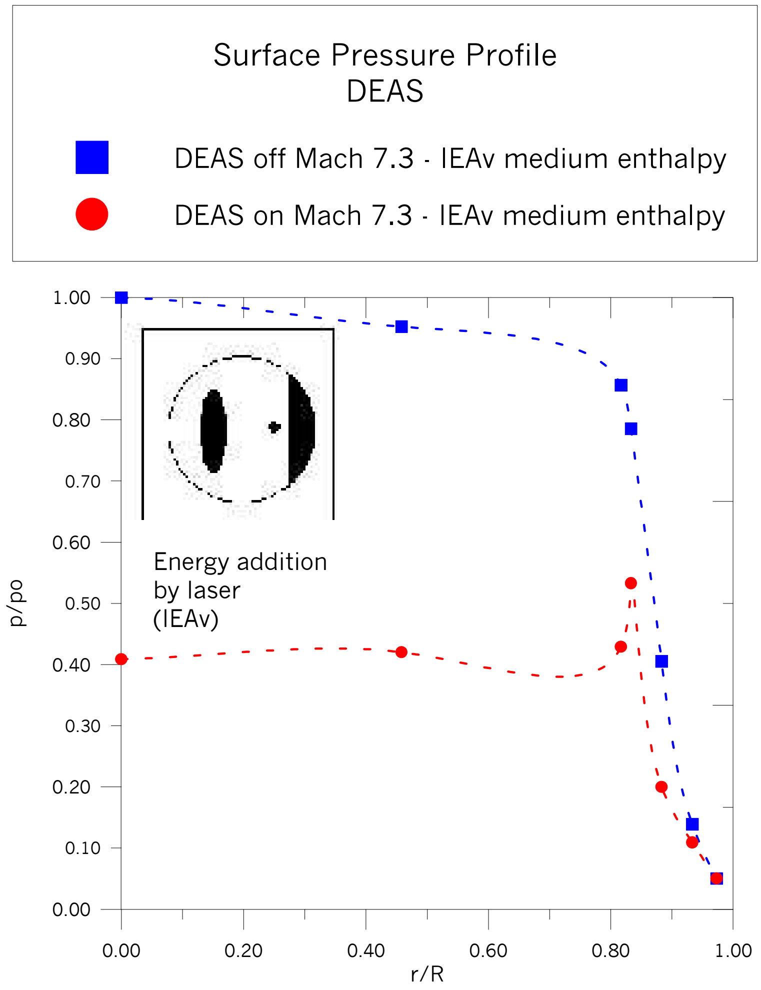

Fig. 5 Surface pressure distribution over the Double Apollo Disc model by laser energy addition (present) and by plasma torch.[10-11]

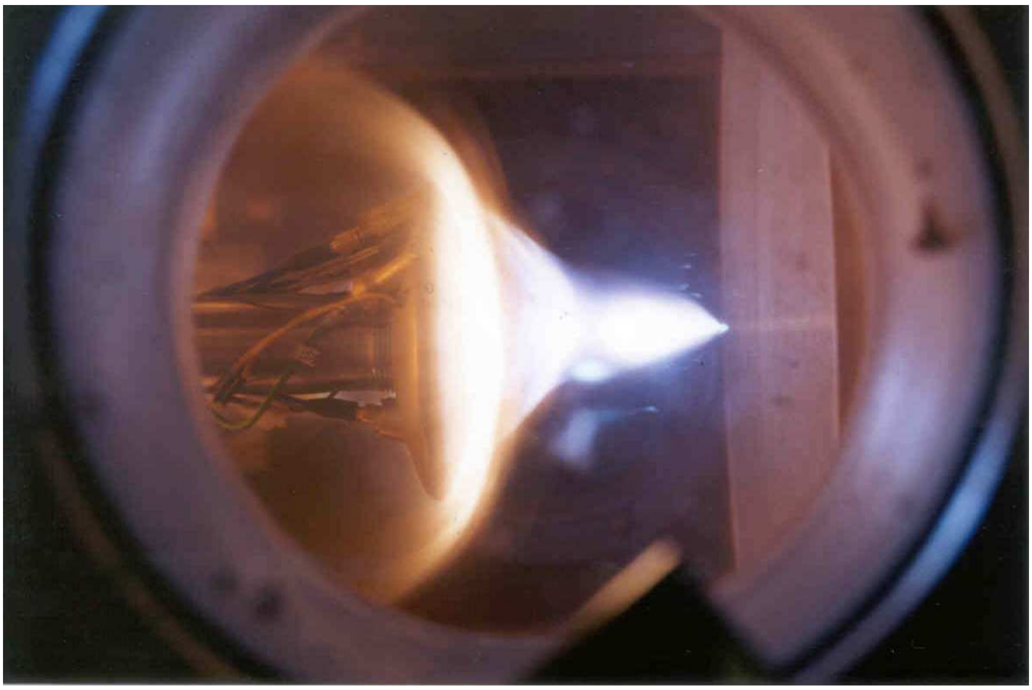

Fig. 6 Open shutter photograph of the laser-induced air ignition in Mach 7.3 flow and of the strong normal and weak conical shock structures in front of the model.

Double Laser Pulse Results

For the shock tunnel conditions presented in Table 1, and the lasers conditions shown in Table 2, the Double Apollo Disc model, Fig. 4, was also tested when two lasers induced air breakdown were generated during the test time. In the present report, the laser pulses were set 50 μs apart but different time intervals can be used.

A great deal of effort was put into getting the two TEA CO_2 lasers, sharing the same optical cavity and active medium, to work. Since the pulse period of each individual TEA laser was much lower then the shock tunnel useful test time, the laser units had to be combined so that a high frequency operation could be achieved and two laser pulses could be generated within the test time available. After overcoming many unexpected problems, such as arcing between electrodes, stable operation was achieved when adequate laser optics were adopted.

Surface pressure measurements could not be made at the time the present paper was prepared due to problems with the piezoelectric pressure transducers. As with the single pulse experiments, a time-lapse photograph of the two-laser pulse experiment was taken with a digital Nikon D-1H camera. This photograph is shown in Fig. 7.

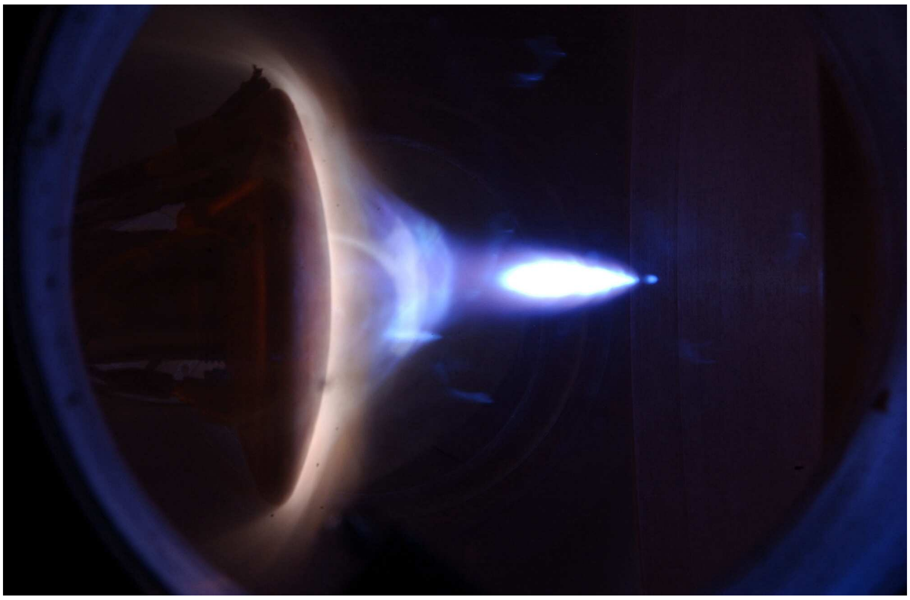

Fig. 7. Digital time-lapse photograph of the two-laser pulse experiment.

4. CONCLUSIONS

Experiments to further investigate the laser supported DEAS concept in and Mach 7.3 flow were conducted in the IEAv 0.3 m Hypersonic Shock Tunnel. Two CO_2 TEA lasers were used to drive either single or double air ignitions upstream of a model fitted with seven pressure transducers was tested. In the single air ignition case, a drop in the surface pressure was observed on most of the model front surface when laser-supported DEAS was on. An increase in the surface pressure was also noticed near the model periphery but its contribution to the aerodynamic drag is negligible. The net result was a lower surface pressure over the model indicating a decrease in the net drag. In the double air ignition case, problems with the pressure transducers precluded surface pressure measurements. Time-integrated type photographs have shown a parabolic flow structure superimposed to the bow shock wave standing in front of the Double Apollo Disc model..

5. ACKNOWLEDGMENTS

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