

Experimental Hypersonic Investigation of the DEAS Concept

Marco Antonio Sala Minucci

sala@ieav.cta.br

Paulo Gilberto de Paula Toro

toro@ieav.cta.br

Antonio Carlos de Oliveira

acoc@ieav.cta.br

José Brosler Chanes Jr.

brosler@ieav.cta.br

Instituto de Estudos Avançados (IEAv / CTA)
Rodovia dos Tamoios km 5,5
São José dos Campos, CEP: 12228-840 – Brazil

Antonio Garcia Ramos

Universidade do Vale do Paraíba (UNIVAP/FEAU)
Av. Shishima Hifumi, 2911
São José dos Campos, CEP: 12244-000 – Brazil
agramos@univap.br

Henry T. Nagamatsu

Leik N. Myrabo

myrabl@rpi.edu

Department of Mechanical Engineering, Aeronautical Engineering, and Mechanics
Rensselaer Polytechnic Institute
Troy, NY 12180-3590 – USA

Abstract. The present paper presents experimental results on the Laser-Supported Directed Energy “Air Spike” – DEAS in hypersonic flow achieved by the Laboratory of Aerothermodynamics and Hypersonics – LAH, Brazil. A CO₂ TEA laser has been used in conjunction with the IEAv 0.3m Hypersonic Shock Tunnel - HST to demonstrate the Laser-Supported DEAS concept. A single laser pulse generated during the tunnel useful test time was focused through a NaCl lens ahead of an aluminum hemisphere-cylinder model fitted with a piezoelectric pressure transducer at the stagnation point. In the more recent experiments, the simple hemisphere-cylinder model was substituted by a Double Apollo Disc model. In this case, two CO₂ TEA lasers, sharing the same optical cavity, have been used in conjunction with the same IEAv 0.3m Hypersonic Shock Tunnel. Single and double laser pulses, generated during the tunnel useful test time, were focused through a NaCl lens upstream of a Double Apollo Disc model fitted with seven piezoelectric pressure transducers. The time-integrated type photographs of the luminous air flow around the model and of the laser-induced air ignition as well as the sequence of frames that shows more detailed history of the generation and the extinction of the Laser-Supported DEAS are presented.

Keywords: Directed-Energy Air Spike, Experimental Hypersonic flow, Hypersonic Shock Tunnel, Flow visualization.

1. Introdução

It has been suggested by several authors (Myrabo, 1978; Tidman, 1990; Myrabo and Raizer, 1994; Head, 1994; Seo, 1994; Gurijanov, 1996; 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. Such energy addition could be accomplished by a plasma torch mounted at the nose of the TAV (Marsh, 1995; Marsh, 1996; Toro, 1998; Toro et al., 1999a and b), by an electric breakdown ahead of the TAV (Minucci et al., 2000a; Bracken et al., 2000; Bracken et al., 2001a and b; Bracken et al., 2002) or by focusing a powerful laser (or microwave) beam ahead of the TAV flight path, as it has been originally suggested by Myrabo and Raizer in 1994, and demonstrated by Minucci et al. (2000b 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.



Figure 1. Conceptual Lightcraft TAV using the DEAS effect.

The first experimental confirmation of such effect came in 1996 when a model of the proposed TAV, fitted with an electric arc plasma torch, was tested in the Rensselaer Polytechnic Institute, RPI, 0.6-m. Hypersonic Shock Tunnel (Marsh, 1995; Marsh, 1996).

In these tests, the laser focus was represented by air plasma at the tip of the slender plasma torch mounted at the model centerline. It was observed that when the plasma torch was turned on at 35 kW, the conical shock wave, originating at the tip of the plasma torch (without the electric arc), would assume a parabolic shape indicating a change in the hypersonic, Mach 10, flow, due to the energy addition. Continuing Marsh's (1995, 1996) exploratory work, Toro (Toro, 1998; Toro et al., 1999a and b) extended the DEAS experimental investigation by measuring both the surface pressure distribution and the surface heat transfer distribution for several plasma torch power levels. The results once more corroborated Myrabo and Raizer (1994) predictions but the presence of the torch itself would make it difficult to completely isolate the torch assembly beneficial effects from those of the energy addition.

To isolate the above-mentioned effects and to more closely simulate the focusing of a laser beam (or a microwave beam) ahead of the model, the torch assembly had to be eliminated. To that end, Minucci (Minucci et al., 2000a; Bracken et al., 2000) suggested that establishing an electric arc between two slender 1.5 mm diameter tungsten electrodes, mounted at the exit plane of the hypersonic shock tunnel conical nozzle, could perform the energy addition to the flow. In this way, the electrodes would be thin enough not to disturb the hypersonic flow and, at the same time, would eliminate the need to use the torch mounting. This experiment is still in progress but has already produced some interesting results (Bracken et al., 2001a and b; Bracken et al., 2002).

The next natural step, which constituted the motivation for the exploratory work (Minucci et al. 2000b to 2001a and 2001b) and the recent investigation carried out at Laboratory of Aerothermodynamics and Hypersonics, LAH (Minucci et al. 2002 and 2003a and 2003b), was to use a laser beam to drive the DEAS, as suggested by Myrabo and Raizer (1994). 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.

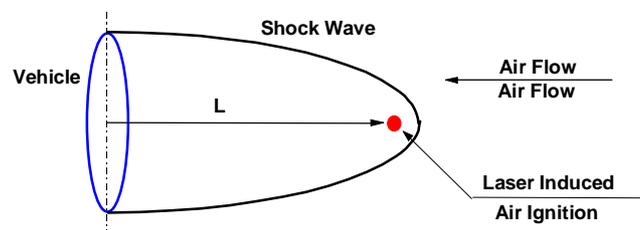


Figure 2. Schematic of the DEAS concept.

A very unique optical method for generating localized and controlled perturbations has been developed for use in supersonic and hypersonic flowfields. The thermal spot disturbance is generated when the pulsed beam from a laser is focused at the desired origin and a small region of the gas is ionized. After recombination, the thermal spot persists as a region of heated gas that convects with the local flow velocity. Nevertheless, the baseline of the present paper is to provide better scientific experiments to corroborate Myrabo and Raizer DEAS concept (1994)³ 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.

2. Experimental Apparatus

The Laser-Supported DEAS experiments were conducted at the Laboratory of Aerothermodynamics and Hypersonics, LAH, in Brazil. The IEAv 0.3-m. Hypersonic Shock Tunnel, Fig. 3, was used to produce high and low enthalpy hypersonic flow conditions. 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 500 μ s and reservoir conditions of 5,000 K and 120 bar. In the low enthalpy case, air was used as the driver gas to produce a useful test time of about 1.5 ms and reservoir conditions of 950 K and 25 bar. 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° half angle and 300 mm exit diameter, nozzle with a throat diameter of 22.5 mm 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.



Figure 3. HST test section and the CO₂ TEA laser heads.

One of the tunnel test section access windows had to be modified to accommodate the laser beam delivery system. This system consisted of a 50 mm 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° 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, the air plasma, created in the focal point, tends to propagate towards the laser source and thus, the energy addition region is not symmetrical with respect to the nozzle centerline.

A Transversely Excited Atmospheric pressure, TEA, Carbon Dioxide Laser, designed and built by Watanuki et al. (1988), was used to drive the DEAS. The laser, in multimode operation, is capable of producing a single high energy, 7.5 J, short, 120 ns (FWHM), laser pulse at 10.6 μ m, wavelength. The output beam has a rectangular cross section, 34 mm x 17 mm.

Figure 3 shows the two CO₂ TEA laser heads, the beam delivery system and the hypersonic shock tunnel test section. Figure 4 shows a drawing of the beam delivery system mounted to the test section access window. The experimental set up, for the double laser pulses, is shown in Fig. 5.

The laser pulse was synchronized with the shock tunnel useful test time via a time delay generator triggered from a Kistler piezoelectric pressure transducer model 701A, located immediately upstream the nozzle entrance. Three Hamamatsu Ge photodiodes model B1720-02, as indicated in Fig. 5, were used as light sensors to monitor the generation of the laser pulse inside the laser head (sensor # 3), the production of the laser induced air ignition (laser-induced breakdown in air) inside the test section (sensors # 1 and 2) and the natural air luminosity of the

hypersonic/hypervelocity flow around the model (sensor # 2). Two additional Kistler pressure transducers model 701A, 0.5 m apart, located in the tunnel driven section, were used to time the incident shock wave.

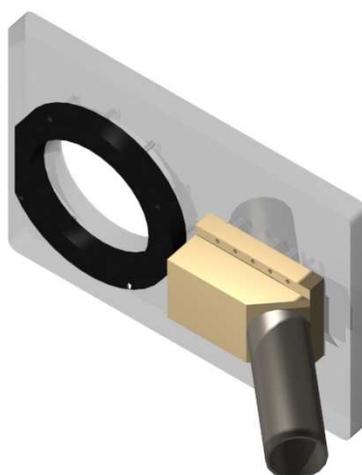


Figure 4. Infrared laser beam delivery system mounted to the shock tunnel test section access window.

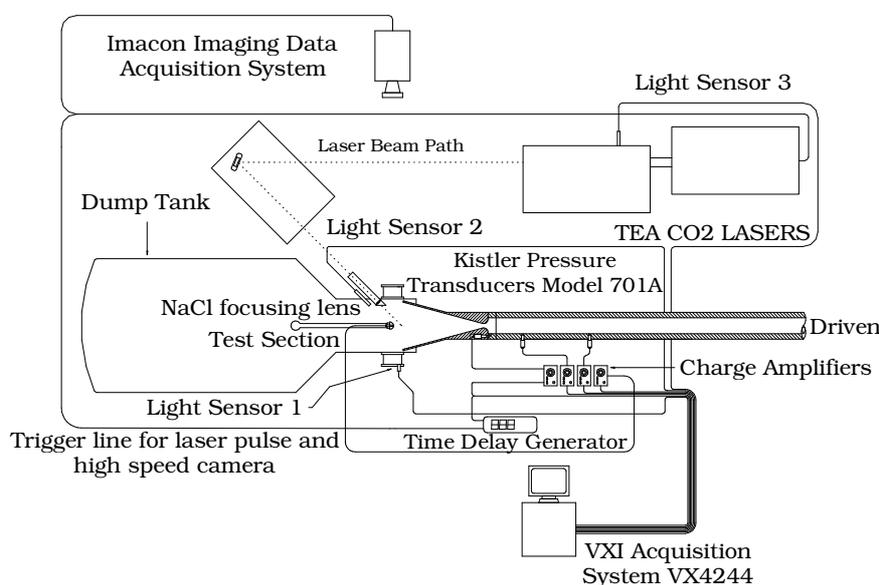


Figure 5. Experimental set up.

In the previous experimental results the time-integrated 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. In some selected tests, an ultra high-speed camera, Hadland Imacon 790 was used to investigate the generation and the extinction of the air ignition in the hypersonic flow. The high-speed camera was triggered simultaneously with the laser pulse and was set with a pre-trigger acquisition time of 0.5 s and a post-trigger acquisition time of 0.5 s. In the more recent investigation an ultra high-speed camera, Hadland Imacon 790 was used for flow visualization.

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

In the preliminary experiments, a very simple model consisting of an aluminum hemisphere-cylinder 55 mm in diameter was mounted 60 mm downstream of the laser focal point. The model was fitted with a Kistler piezoelectric pressure transducer model 701A, at the stagnation point, so that the impact pressure downstream of the laser-driven air breakdown could be recorded. A centerline cylindrical channel, 4.5 mm long and 2 mm in diameter, connected the pressure transducer diaphragm to the model surface.

In order to obtain more detailed pressure information a new model was designed and built. This model has the same geometry as that currently under investigation (electric arc - driven DEAS) by Rensselaer Polytechnic Institute - RPI researchers, i.e., Double Apollo Disc configuration. A photograph of the actual model, installed in the shock tunnel test section, is shown in Fig. 6. Figure 7 depicts an artist view of the model installed in the tunnel test section. The 100 mm

diameter model houses pressure transducers, as indicated in Fig. 6, and it is positioned 100 mm downstream of the air ignition, Fig. 7.

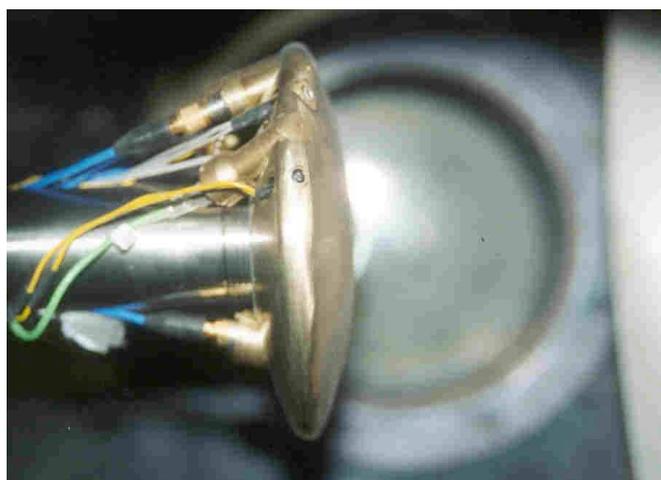


Figure 6. Photograph of the instrumented Double Apollo models.

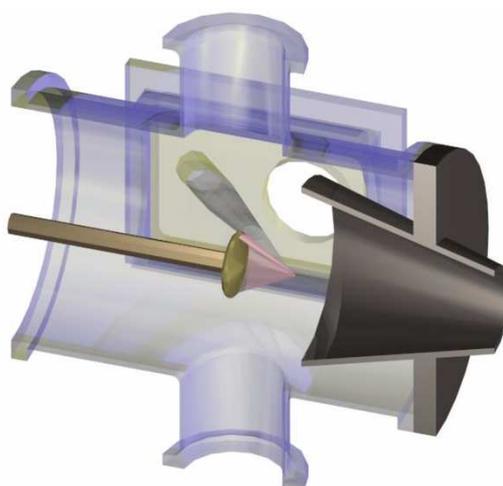


Figure 7. The Double Apollo Disc model in the IEAv HST test section.

3. Results and Discussion

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

Table 1 Shock Tunnel Test Conditions.

		High Enthalpy	Medium Enthalpy	Low Enthalpy
Reservoir	Pressure (bar)	120.0	173.0	25.0
	Temperature (K)	5,000.0	1,685.0	950.0
Conditions	Enthalpy MJ/kg)	9.0	1.9	1.0
	Pressure (mbar)	12.0	23.2	4.0
Free Stream Conditions	Temperature (K)	1,000	158.4	77.0
	Density (g/m ³)	4.0	51.1	17.0
	Mach Number	6.2	7.3	7.8
	Test Time (milliseconds)	≈ 0.5	≈ 1.0	≈ 1.5

Table 2 CO₂ 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

3.1 Previous Results

From Table 1 it is quite evident that the static pressures present in the hypersonic flow at the nozzle exit were quite low. As a consequence, the authors were expecting some difficulty in generating air ignition (laser-induced breakdown in air) under these conditions, for the laser energy available shown in Table 2. However, it was experimentally observed that, for the high enthalpy runs, laser-induced air breakdown would always take place in the low-pressure conditions existing in the hypersonic flow upstream of the model. At first, the present authors were lead to believe that the air ignition was being triggered by particles/debris contaminating the high-speed flow. Once the low enthalpy tests were performed, and the laser-induced air breakdown could not be obtained as easily as in the high enthalpy case, the particle contamination idea became uncertain. Since the same type of test gas, in the present case air, was used in both high and low enthalpy tests, any contaminants that could trigger the air ignition were present in both scenarios. The authors then suspect that probably a combination of a high static temperature, 1,000 K, and non-equilibrium effects present in the flow could be responsible for the successful laser-induced air ignition at these low static pressures.

Figures 8 and 9 show typical model impact pressure trace (located at stagnation point of the model), for the DEAS off (Fig. 8) and for the DEAS on (Fig. 9), as well as the output traces from light sensors # 1 (the production of the laser induced air ignition inside the test section) and # 3 (the generation of the laser pulse inside the laser head).

Light sensor # 3 clearly indicates the moment the TEA laser fired by recording the luminosity coming out from the laser cavity electric discharge. On the other hand, the natural air luminosity of the hypervelocity flow around the model, as well as the luminosity of the laser-induced air breakdown, can be seen in the output trace from light sensor # 1 (for the case of DEAS off there is no luminosity of the laser-induced air breakdown). The impact pressure trace shows a vibration noise, which could not be eliminated during the tests. The authors suspect the vibration noise is due to the combination of the pressure transducer installation (the pressure transducer is installed inside of recess mounting hole as recommended by the manufacturer) and laser-induced air breakdown (the ringing of the cavity when excited by the thermal spot disturbance).

Interestingly enough, the impact pressure (from the pressure transducer installed at stagnation point of the model) trace seems to show the effect of the laser-induced air breakdown. Shortly after the air ignition is generated, a high frequency “ringing” indicates the impact of the detonation wave against the model front surface and a drop in pressure occurs. This drop in the impact pressure coincides with the duration of the air ignition and may indicate a decrease in the aerodynamic pressure drag caused by the DEAS effect. This trend, however, is going to be corroborated by more recent tests to be discussed in the next section.

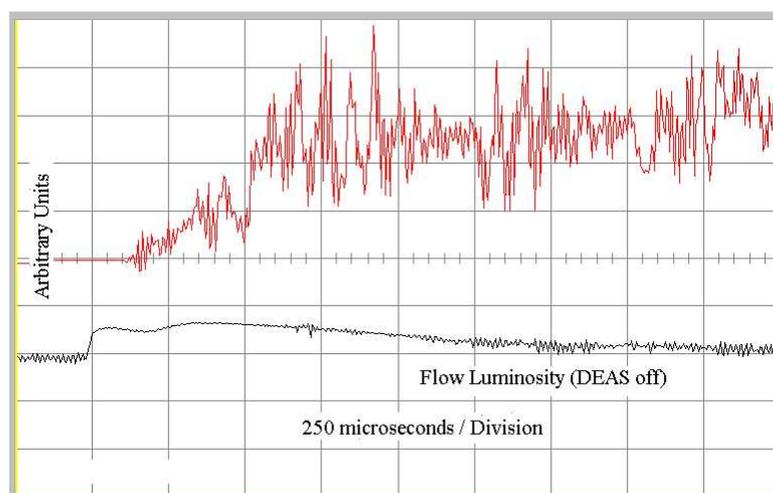


Figure 8. Typical high enthalpy impact pressure (top), light sensor # 1 (bottom) traces.

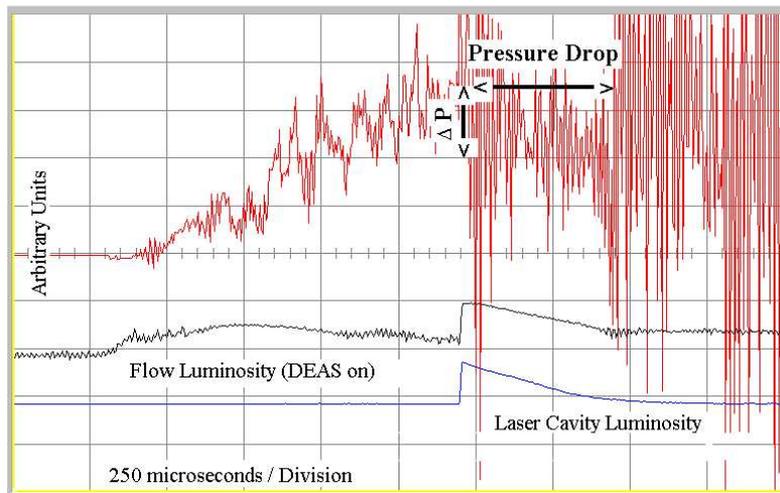


Figure 9. Typical high enthalpy impact pressure (top), light sensor # 1 (middle) and light sensor # 3 (bottom) traces.

As stated previously, low enthalpy tests were also conducted with the hemisphere-cylinder model but no consistent laser-induced air ignition was ever achieved. As a consequence, no change in the impact pressure was verified.

Figure 10 shows a time-integrated photograph of the laser-induced air breakdown upstream of the model at Mach 6.2 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-integrated 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. 10 both the bow shock in front of the model and the parabolic flow structure upstream of it.

The parabolic flow structure seen in Fig. 10 seems to agree with the impact pressure drop observed in Figures 8 and 9 and also with the DEAS mechanism proposed by Myrabo and Raizer (1994). 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 parabolic flow structure seen in Fig. 10 and its schematic view, Fig. 2. This flow structure creates a parabolic-shaped shock wave well ahead of hemisphere.

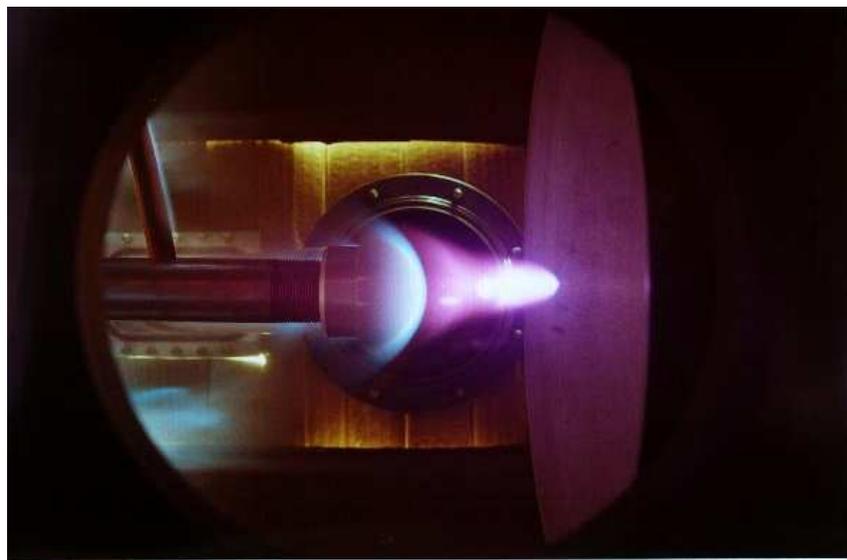


Figure 10. Open shutter photograph of the laser-induced air ignition in Mach 6.2 flow and of the strong normal and weak conical shock structures in front of the model.

3.2 Present Results – Single Laser Pulse Results

For the medium enthalpy conditions present in Table 1, and the conditions show in Table 2, a more instrumented model shown in Fig. 6 was tested. Surface pressure measurements can be found in Fig. 11. Such pressure measurements

are non-dimensionalized by the impact pressure (pressure transducer installed at the stagnation point of the model) 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 (energy addition by laser, IEAv). As a consequence, the laser-supported DEAS was able to generate a decrease in the surface pressure over the new model tested and, therefore, a considerable decrease in the aerodynamic drag. This result is in agreement to that obtained with the simple hemisphere-cylinder model discussed earlier in the present paper. On the other hand, a surface pressure increase was detected near the model periphery. Although the contribution of such pressure increase to the aerodynamic drag is minimal, it is an interesting behavior since, as stated previously, such configuration may be used as an annular air inlet. The same behavior was observed by Toro (1998, 1999a), Fig. 11, using a plasma torch and the same model geometry (energy addition by plasma torch, RPI). Toro et al. (1998, 1999a), experiments were performed at Mach number 10 low enthalpy with 770 K stagnation temperature and 127 kW power added at the tip of the plasma torch. Additional testing may reveal whether increasing the distance from the model front surface to the air ignition location can minimize this pressure increase.

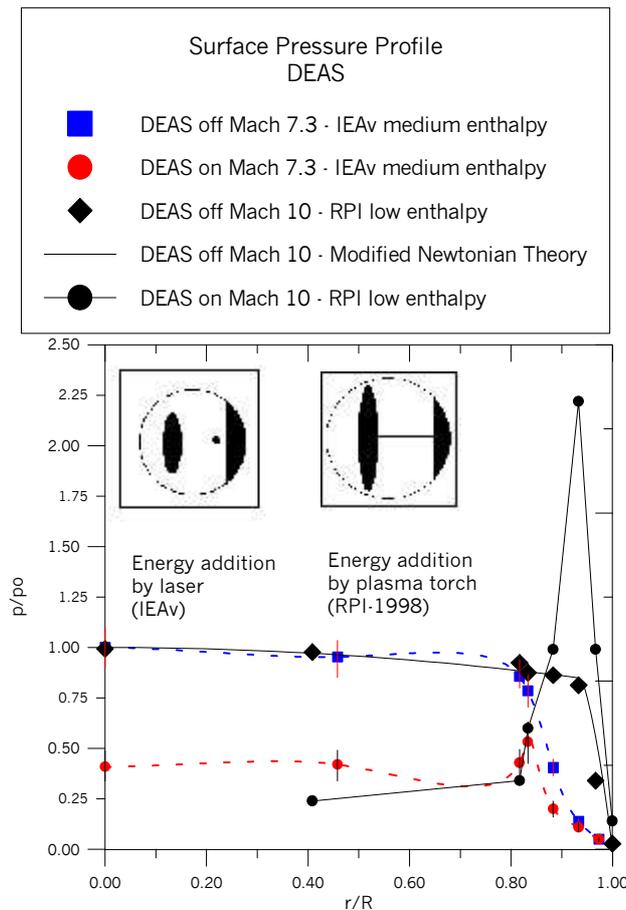


Figure 11. Surface pressure distribution over the Double Apollo Disc model by laser energy addition (present) and by plasma torch (Toro et al., 1998, 1999a).

A very detailed history of the generation and the extinction of the Laser-Supported DEAS were obtained through the use of the ultra high speed Hadland Imacon 790, shown in Fig. 12. The camera was triggered by a pressure transducer upstream of the nozzle entrance as shown in Fig. 5, and operated at 100,000 frames per second. The exposure time of each frame was 2 μ s resulting in a total of 10 frames each one taken every 10 μ s. All 10 frames were recorded onto a single Polaroid 667 film. In order to facilitate the understanding of the sequence of events the film was digitized and each individual frame displayed in chronological order. In Fig. 13, the darkened areas seen in the two first frames (as well as in the two last frames) correspond to the edge of the camera recording phosphor screen. The positions of the model surface and the laser focal point are indicated in the inset in Fig. 12. In the two first frames only the luminosity of the bow shock wave over the model surface is seen. The third frame depicts the moment of the laser breakdown. In the next 4 frames one can see the resulting plasma being pushed against the model surface and the parabolic flow structure established ahead of it. Finally, in the last three frames it is visible the extinction of the DEAS and something that resembles re-establishment of the original bow shock wave.

Figure 13 shows a time-integrated 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 pressure transducer cables, the nozzle exit. Since it is a time-integrated 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. 13 both the bow shock in front of the model and the parabolic flow structure upstream of it.

The parabolic flow structure seen in Fig. 13 seems to agree with the DEAS mechanism proposed by Myrabo and Raizer (1994). 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 parabolic flow structure seen in Fig. 13. This flow structure creates a detached parabolic-shaped shock wave well ahead of model.

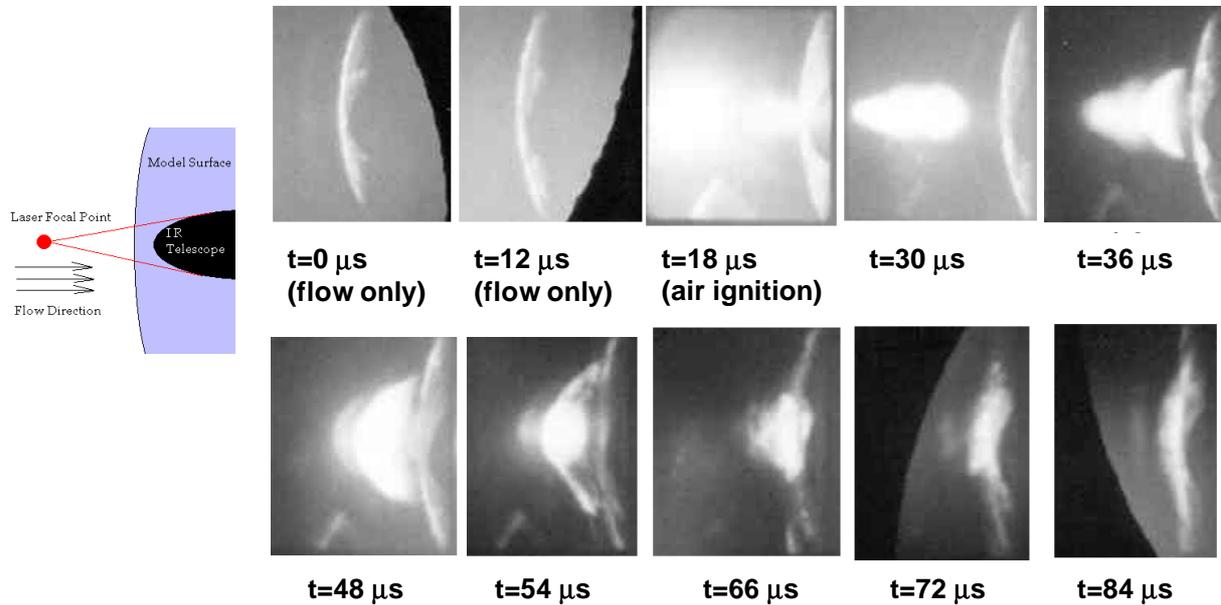


Figure 12. Time history of the generation and extinction of the laser-supported DEAS in medium enthalpy flow.

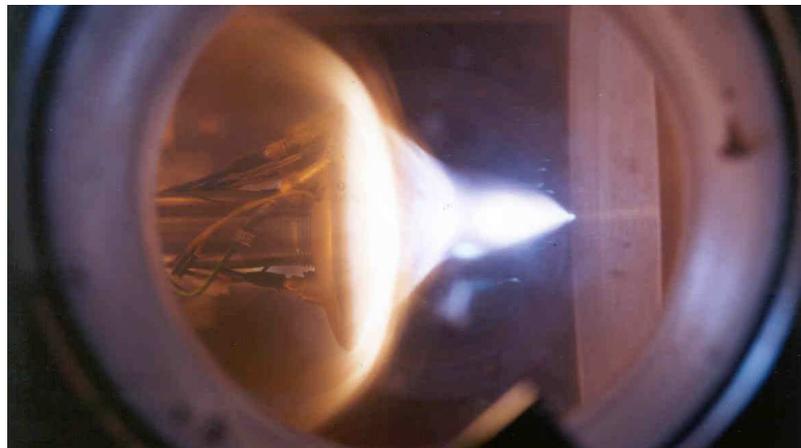


Figure 13. Open shutter photograph of the laser-induced air ignition in Mach 7.3 flow and of the strong normal and weak conical shock structures in front of the model.

3.3 Present Results – Double Laser Pulse Results

For the shock tunnel conditions presented in Table 1, and the lasers conditions shown in Table 2, the Apollo double disc model, Fig. 6, was also tested when two laser induced air breakdowns were generated during the test time. In the present report, the laser pulses were set 50 μ s apart but different time intervals can be used.

A great deal of effort was put into getting the two TEA CO₂ lasers, sharing the same optical cavity and active medium, to work. Since the pulse period of each individual TEA laser was much lower than 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.

A detailed history of the generation and the extinction of two Laser-Supported DEAS was obtained through the use of the ultra high speed Hadland IMACOM 790. Due to a camera malfunction the last frames were superimposed and the viewing area was reduced. The digitized sequence of frames is shown in Fig. 14.

In Fig. 14, the darkened areas seen in the last two frames correspond to the edge of the camera recording phosphor screen. The positions of the model surface and the laser focal point are indicated in the inset in Fig. 14. In the first frame only the luminosity of the bow shock wave over the model surface is seen. The second frame depicts the moment of the first laser induced air breakdown. In the next 5 frames one can see the resulting plasma being pushed against the model surface, the parabolic flow structure established upstream of it and its extinction. Then, the second laser induced air breakdown is recorded in the 8th frame. The remaining 4 frames show again the resulting plasma being pushed against the model surface, the formation of a new parabolic flow structure and the onset of its extinction. The flow reestablishment cannot be observed due to the limited number of frames available.

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. 15.

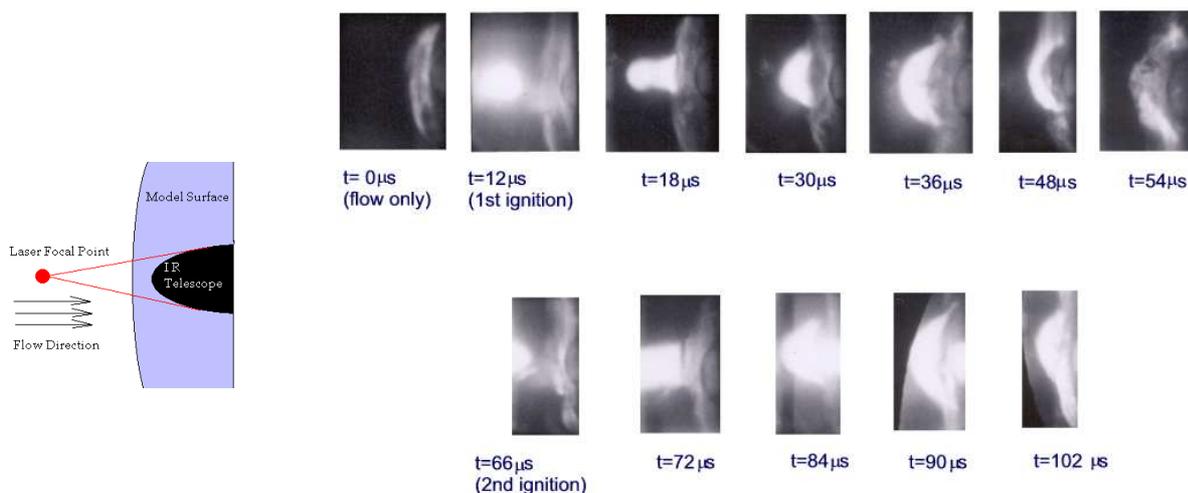


Figure 14. Time history of the generation and extinction of two laser-supported DEAS in medium enthalpy flow.

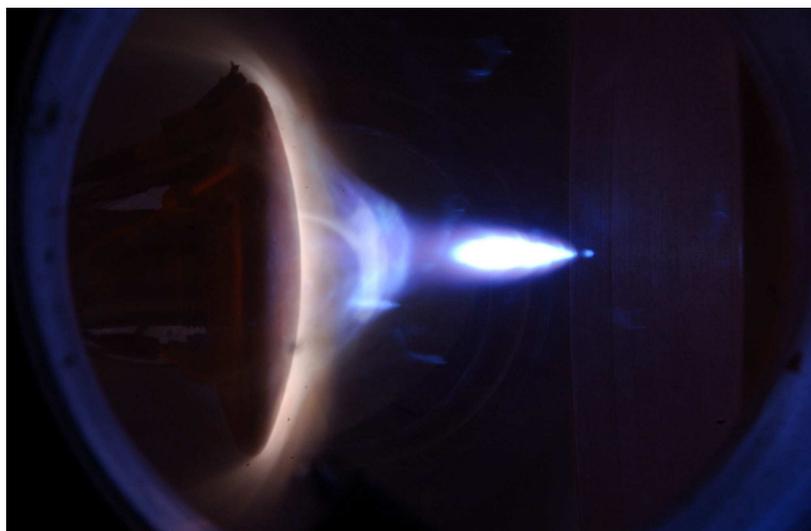


Figure 15. Digital time-lapse photograph of the two-laser pulse experiment.

4. Conclusions

Preliminary experiments to demonstrate the laser supported DEAS concept in Mach 6.2 flow (real air) and Mach 7.3 flow (ideal air) were conducted in the IEAv 0.3-m. Hypersonic Shock Tunnel. A CO₂ TEA laser was used to drive the air ignition upstream of a hemisphere-cylinder installed in the modified shock tunnel test section. It was observed that, for the high enthalpy reservoir conditions, the laser-induced air ignition could be established consistently in spite

of the low static pressures present in the hypersonic/hypervelocity airflow. A piezoelectric pressure transducer, installed at the stagnation point of the model, indicated a drop in the impact pressure that coincided with the duration of the luminosity generated by the laser-induced air breakdown. Time-integrated type photographs have shown a parabolic flow structure superimposed to the bow shock wave standing in front of the hemisphere-cylinder. Low enthalpy, ideal air, runs were also performed but the laser-supported air ignition could not be established either consistently or completely.

In order to further investigate the laser supported DEAS and to corroborate the promising results herein presented, a new model, fitted with seven pressure transducers were built. The geometry of the model is the same as the one has been tested by RPI researchers using an electric arc discharge to drive the DEAS. A drop in the surface pressure distribution 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, when compared to the one of the recirculation region. The net result was a lower surface pressure over the model indicating a decrease in the net drag. The dynamics of the formation of the parabolic flow structure was revealed through the use of a high-speed camera.

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 CO₂ TEA lasers were used to drive either single or double air ignitions upstream of a model fitted with seven pressure transducers. The geometry of the model is the same as the one being tested by RPI researchers using an electric arc discharge to drive the DEAS. The high speed photography indicated that two laser induced air breakdowns were successfully generated, upstream of the model, during the hypersonic shock tunnel useful test time. More experiments and flow visualization are needed to better understand the phenomenon.

5. ACKNOWLEDGMENTS.

The authors would like to express their gratitude to Dr. Laurentino C. V. Neto and Mr. André L. Pereira for their invaluable support.

6. References.

- Bracken, R.M., Myrabo, L.N., Nagamatsu, H.T., Meloney, E.D., and Minucci, M.A.S., 2000, "Arc Simulated "Air-Spike" in the RPI Hypersonic Shock Tunnel at Mach 10 and Arc powers up to 11MW," 7th International Workshop on Shock Tube Technology, Long Island, NY, September.
- Bracken, R.M., Myrabo, L.N., Nagamatsu, H.T., Meloney, E.D., and Shneider, M.N., 2001a, "Experimental Investigation of an Electric Arc Air-Spike With and Without Blunt Body in Hypersonic Flow," AIAA Paper 2001-0796, 39th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, January.
- Bracken, R.M., Myrabo, L.N., Nagamatsu, H.T., Meloney, E.D., and Shneider, M.N., 2001b, "Experimental Investigation of an Electric Arc Air-Spike in Mach 10 Flow with Preliminary Drag Measurements," AIAA Paper 2001-2734, 37th AIAA/ASME/ASEE Joint Propulsion Conference & Exhibit, Los Angeles, CA, June.
- Bracken, R.M., Hartley, C.S., Mann, G., Myrabo, L.N., Nagamatsu, H.T., Shneider, M.N. and Raizer, Y.P., 2002, "Experimental and Computational Investigation of Hypersonic Electric-Arc Airspikes," 1st International Symposium on Beamed Energy Propulsion, Editor Andrew V. Pakhomov, pp. 485-496, American Institute of Physics.
- Covault, G., 1999, "'Global Presence' Objective Drives Hypersonic Research," Aviation Week & Space Technology, pp. 54-58, April.
- Gurijanov, E.P., and Harsha, P.T., 1996, "AJAX: New Directions in Hypersonic Technology," AIAA Paper 96-4609.
- Head, S.R., 1994, "Theoretical Analysis of the Hypersonic 'Air-Spike' Inlet," MS Thesis, Rensselaer Polytechnic Institute, Department of Mechanical Engineering, Aeronautical Engineering, and Mechanics, August.
- Marsh, J.J., 1995, "An Experimental Investigation of the Hypersonic "Air Spike" Inlet, MS Thesis, Rensselaer Polytechnic Institute, Department of Mechanical Engineering, Aeronautical Engineering, and Mechanics, May.
- Marsh, J.J., Myrabo, L.N., Messitt, D.G., and Nagamatsu, H.T., 1996, "Experimental Investigation of the Hypersonic "Air Spike" Inlet at Mach 10," AIAA Paper 96-0721, 34th Aerospace Sciences Meeting & Exhibit, Reno, NV, January.
- Minucci, M.A.S., Bracken, R.M., Myrabo, L.N., Nagamatsu, H.T., and Shanahan, K.J., 2000a, "Experimental Investigation of an Electric Arc Simulated "Air Spike" in Hypersonic Flow," AIAA Paper 00-0715, 38th Aerospace Sciences Meeting & Exhibit, Reno, NV, January.
- Minucci, M.A.S., Toro, P.G.P., Chanes Jr, J.B., Ramos, A.G., Pereira, A.L., Nagamatsu, H.T. and Myrabo, L.N., 2000b, "Experimental Investigation of a Laser-Supported Directed-Energy "Air Spike" in Hypersonic Flow – Preliminary Results," 7th International Workshop on Shock Tube Technology, Long Island, NY, September.
- Minucci, M.A.S., Toro, P.G.P., Chanes Jr, J.B., Pereira, A.L., Nagamatsu, H.T. and Myrabo, L.N., 2001a, "Investigation of a Laser-Supported Directed-Energy "Air Spike" in Mach 6.2 Air Flow – Preliminary Results," 39th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, January.

- Minucci, M.A.S., Toro, P.G.P., Chanes Jr, J.B., Ramos, A.G., Pereira, A.L., Nagamatsu, H.T. and Myrabo, L.N., 2001b, "Recent Developments on the Laser-Induced Air Spike in Hypersonic Flow," 23rd International Symposium on Shock Waves, Fort Worth, TX, July.
- Minucci, M.A.S., Toro, P.G.P., Chanes Jr, J.B., Ramos, A.G., Pereira, A.L., Nagamatsu, H.T. and Myrabo, L.N., 2002, "Brazilian Activities on the Laser-Supported DEAS in Hypersonic Flow," 1st International Symposium on Beamed Energy Propulsion, Editor Andrew V. Pakhomov, pp. 497-508, American Institute of Physics.
- Minucci, M.A.S., Toro, P.G.P., Chanes Jr, J.B., Ramos, A.G., Pereira, A.L., Nagamatsu, H.T. and Myrabo, L.N., 2003a, "Investigation of a Laser-Supported Directed-Energy 'Air Spike' in Hypersonic Flow," *Journal of Spacecraft and Rockets*, vol. 40, n° 1, pp. 133-136, Jan.-Feb.
- Minucci, M.A.S., Toro, P.G.P., Oliveira, A.C.; Chanes Jr, J.B., Ramos, A.G., Nagamatsu, H.T. and Myrabo, L.N., 2003b, "Multi Laser Pulse Investigation of the DEAS Concept in Hypersonic Flow," 2nd International Symposium on Beamed Energy Propulsion, Japan.
- Myrabo, L.N., 1978, "Solar-Powered Global Air Transportation," *AIAA/DGLR Paper 78-698*, 13th International Electric Propulsion Conference, San Diego, CA, 25-27 April.
- Myrabo, L.N., and Raizer, Yu. P., 1994, "Laser Induced Air Spike for Advanced Transatmospheric Vehicles," *AIAA Paper 94-2451*, 25th *AIAA Plasmadynamics and Lasers Conference*, Colorado Springs, CO, 20-23 June.
- Seo, J., 1994, "Analysis of Aerodynamics Properties Inside Airspike of Microwave Propelled Transatmospheric Vehicle," MS Thesis, Rensselaer Polytechnic Institute, Department of Mechanical Engineering, Aeronautical Engineering, and Mechanics, August.
- Tidman, D. A., 1990, "Apparatus and Method for Facilitating Supersonic Motion of Bodies Through the Atmosphere," *United States Patent Number 4,917,335*, April.
- Toro, P.G.P., 1998, "Experimental Pressure and Heat Transfer Investigation over a "Directed-Energy Air Spike" Inlet at Flow Mach Numbers of 10 to 20, Stagnation Temperature of 1000K, and Arc Power up to 127 kW", Ph.D. Thesis, Rensselaer Polytechnic Institute, Department of Mechanical Engineering, Aeronautical Engineering, and Mechanics, August 1998. Also NASA CR-NCC8-112, August.
- Toro, P.G.P., Nagamatsu, H.T., Minucci, M.A.S., and Myrabo, L.N., 1999a, "Experimental Pressure Investigation of a "Directed-Energy Air Spike" Inlet at Mach 10," *AIAA Paper 99-2843*, 35th *AIAA/ASME/ASEE Joint Propulsion Conference & Exhibit*, Los Angeles, CA, June.
- Toro, P.G.P., Nagamatsu, H.T., Myrabo, L.N., and Minucci, M.A.S., 1999b, "Experimental Heat Transfer Investigation of a "Directed-Energy Air Spike" Inlet at Mach 10," *AIAA Paper 99-2844*, 35th *AIAA/ASME/ASEE Joint Propulsion Conference & Exhibit*, Los Angeles, CA, June.
- Watanuki, J.T., Oliva, J.L.S., Lobo, M.F.G., and Rodrigues, N.A. S., 1988, "Laser de CO₂ -Híbrido com Célula de Baixa Pressão Pulsada," *Revista de Física Aplicada e Instrumentação*, Vol. 3, No. 3, pp.207-216. (in Portuguese).