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Laser-Supported Directed-Energy "Air Spike" in Hypersonic Flow

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The experimental results on the laser-supported directed-energy "air spike" (DEAS) in hypersonic flow are presented. A CO_2 TEA laser has been used in conjunction with the IEAv 0.3-m Hypersonic Shock Tunnel 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, a double Apollo disk model fitted with seven piezoelectric pressure transducers substituted the simple hemisphere-cylinder model. The objective of the present research is to corroborate the past results as well as to obtain additional pressure distribution information.

Introduction

It has been suggested by several authors[1–7] 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,[8–12] by an electric breakdown ahead of the TAV,[13–17] 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[3] in 1994, and demonstrated by Minucci et al.[18–22] and Powell (a disclosure of the first successful directed-energy air spike by laser-energy deposition tests by Minucci et al. in the IEAv Hypersonic Shock Tunnel, Brazil).[23]

Knight et al.[24,25] provide very selective surveys of research in aerodynamic flow control at high speed using steady[24] and unsteady[25] energy deposition (e.g., plasma arcs, laser pulse, microwave, electron beam, glow discharge.) not only for drag reduction applications but also for lift and moment enhancement, improved mixing, modification of shock structure, etc. The surveys review the effect of energy deposition, upstream of a blunt body in supersonic flow, on drag reduction (i.e., integrated frontal surface pressure) when sufficiently high levels of energy deposition were used.[26–30]

Myrabo and Raizer 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 reentry 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.

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.[8,9]

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, as a result of the energy addition. Continuing Marsh's[8,9] exploratory work, Toro and coworkers[10–12] extended the DEAS 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[3] 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 effects just mentioned 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 et al.[13] and Bracken et al.[14] suggested that establishing an electric arc between two slender 1.5-mm-diam 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[13,14] but has already produced some interesting results.[15–17]

The next natural step, which constituted the motivation for the exploratory work[18–20] and the recent investigation carried out at Laboratory of Aerothermodynamics and Hypersonics (LAH),[21–23] was to use a laser beam to drive the DEAS, as suggested by Myrabo and Raizer.[3] 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

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Fig. 1 Conceptual lightcraft TAV using the DEAS effect.

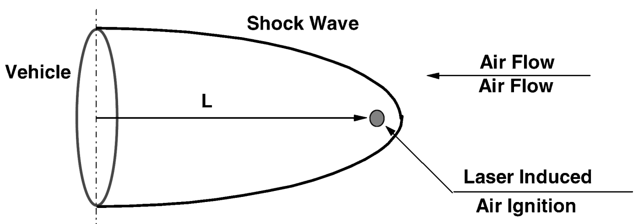


Fig. 2 Schematic of the DEAS concept.

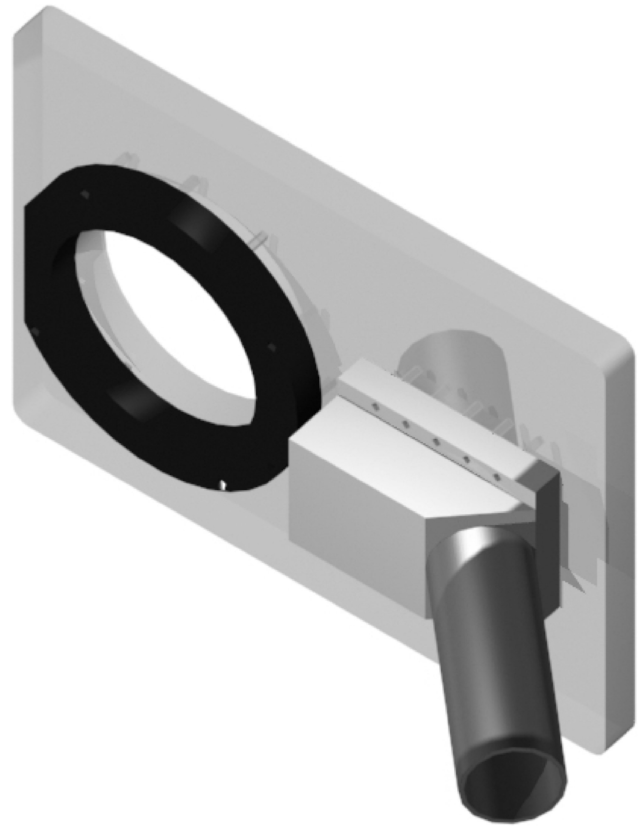


Fig. 3 Infrared laser beam delivery system mounted to the shock-tunnel test-section access window.

from the axial direction and forces it to flow over the air spike to the periphery of the vehicle (Fig. 1).

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.[31] Riggins et al.[32] describe a parametric examination of focused energy deposition into the flow (lasers, microwaves) that could result in very large drag reduction and significant relaxation of a supersonic and hypersonic vehicle shape requirements. A full Navier–Stokes computational-fluid-dynamics code was used to perform a parametric study of energy deposition upstream of a generic two-dimensional and axisymmetric blunt bodies at Mach numbers of 6.5 and 10. The energy deposition modifies the upstream shock structure and results in large wave drag reduction (about 30%) and very high power effectiveness.

Nevertheless, the baseline of the present paper is to provide better scientific experiments to corroborate Myrabo and Raizer's DEAS concept[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 important, 2) it deflects the oncoming hypersonic airflow 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.

Experimental Apparatus

The laser-supported DEAS experiments were conducted at LAH in Brazil. The IEAv 0.3-m Hypersonic Shock Tunnel was used to produce high- and low-enthalpy hypersonic flow conditions.[33,34] 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 μs and reservoir conditions of 5000 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-deg 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.

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-diam 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. Because of geometrical constraints, the telescope had to be installed 45 deg 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,[35] the energy addition region is not symmetrical with respect to the nozzle centerline. Figure 3 shows a drawing of the beam delivery system mounted to the test-section access window.

A transversely excited atmospheric pressure (TEA), carbon-dioxide laser, designed and built by Watanuki et al.[36] was used to drive the DEAS. Figure 4 shows the laser head, the beam delivery system, and the hypersonic shock-tunnel test section. The laser, in multimode operation, is capable of producing a single high-energy, 7.5 J, short, 120-ns, full width half-maximum (FWHM) laser pulse at 10.6-μm wavelength. The output beam has a rectangular cross section, 34 × 17 mm. The experimental setup 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 of the nozzle entrance. Three Hamamatsu Ge photodiodes model B1720-02, as indicated in Fig. 5, were used as light sensors to

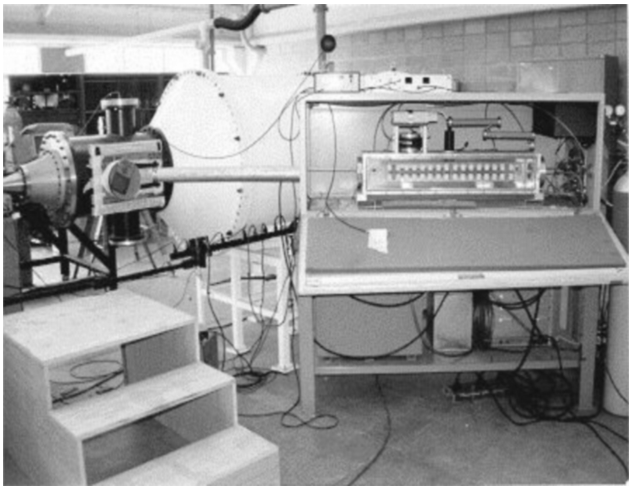


Fig. 4 IEAv 0.30-m Hypersonic Shock Tunnel test section and the CO_2 TEA laser head.

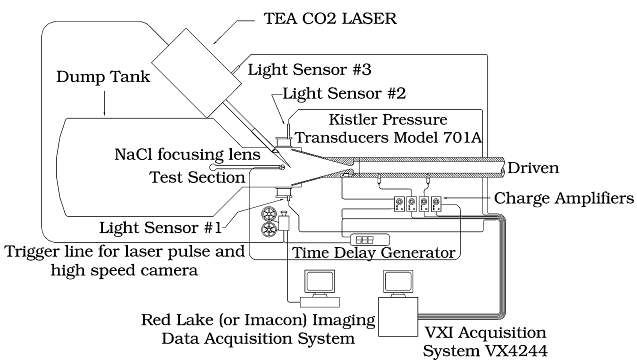


Fig. 5 Experimental setup.

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)[35] 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.

In the previous experimental results the time-integrated type photographs of the luminous airflow around the model and of the laser-induced air ignition were taken by using a Nikon camera Model N6006 with AF35-70-mm f/3.3-f/4.5 Nikkor lenses and ISO 100 color film. In some selected tests, a Redlake high-speed charge-coupled device (CCD) camera model MotionScope PCI 8000S at 8000 fps and a shutter speed of 1/24,000 s 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 pretrigger acquisition time of 0.5 s and a posttrigger 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 of 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, Fig. 6, 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.

To obtain more detailed pressure information, a new model was designed and built. This model has the same geometry as that

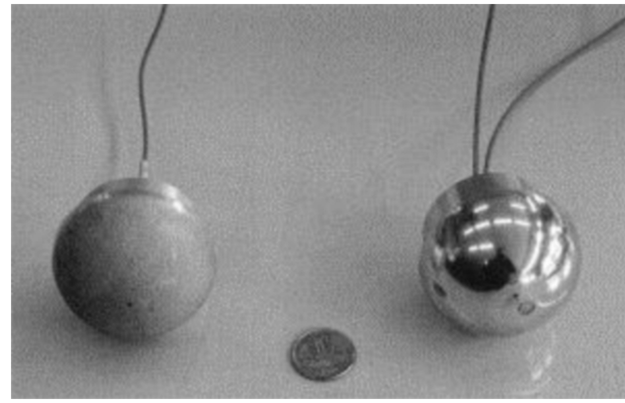
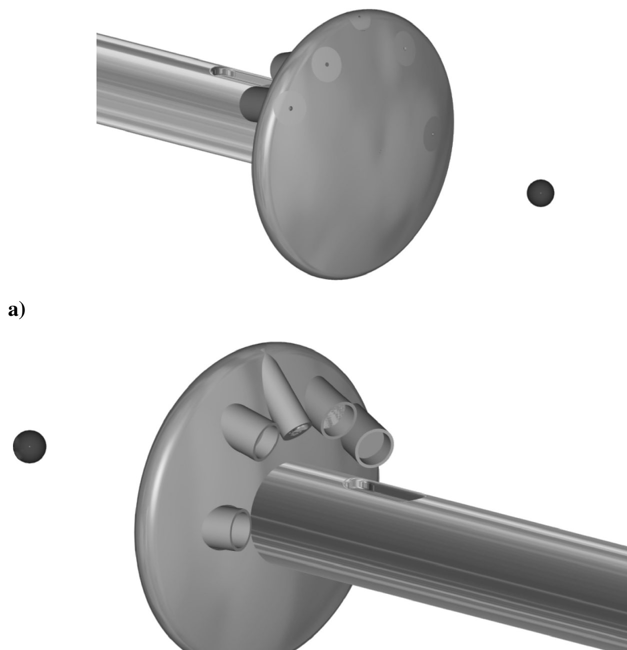


Fig. 6 Hemisphere-cylinder models.



a)

b)

Fig. 7 Double Apollo disk model with a) front and b) rearviews showing the position of the instrumentation: ●, position of the laser focal point.

currently under investigation (electric arc-driven DEAS)[8–12,15–17] by RPI researchers, that is, double Apollo disk configuration. A schematic view of the model, with the instrumentation ports, is shown in Fig. 7, and a photograph of the actual model, installed in the shock tunnel test section, is shown in Fig. 8. Figure 9 depicts an artist's view of the model installed in the tunnel test section. The 100-mm-diam model houses pressure transducers, as indicated in Fig. 7, and it is positioned 100 mm downstream of the air ignition (Fig. 9).

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.

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)[35] under these conditions, for the laser energy available shown in Table 2. However, it was experimentally observed that, for the high-enthalpy runs,

Table 1 Shock-tunnel test conditions

Parameter	High enthalpy	Medium enthalpy	Low enthalpy
Reservoir pressure, bar	120.0	173.0	25.0
Reservoir temperature, K	5000.0	1685.0	950.0
Reservoir enthalpy, MJ/kg	9.0	1.9	1.0
Freestream pressure, mbar	12.0	23.2	4.0
Freestream temperature, K	1000.0	158.4	77.0
Freestream density, g/m^3	4.0	51.1	17.0
Freestream Mach number	6.2	7.3	7.8
Useful test time, ms	0.5	1.0	1.5

Table 2 CO_2 TEA laser operating conditions

Condition	Value
Energy per pulse, J[a]	7.5
Pulse duration, ns	120
Gas mixture	7%CO_2–54%N_2–39%He

[a]Average between the energy meter readings immediately before and after the test.

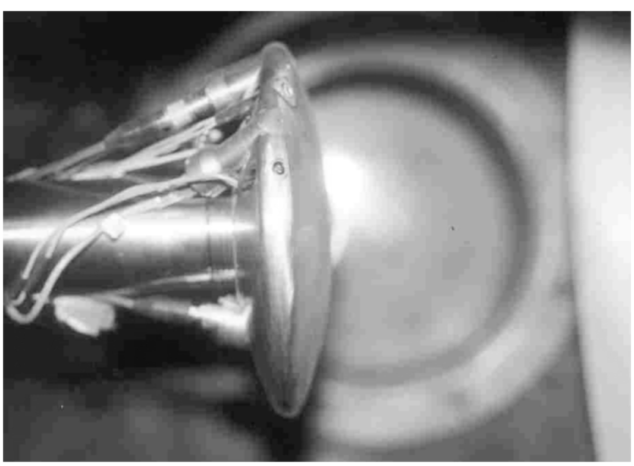


Fig. 8 Photograph of the instrumented double Apollo disk model.

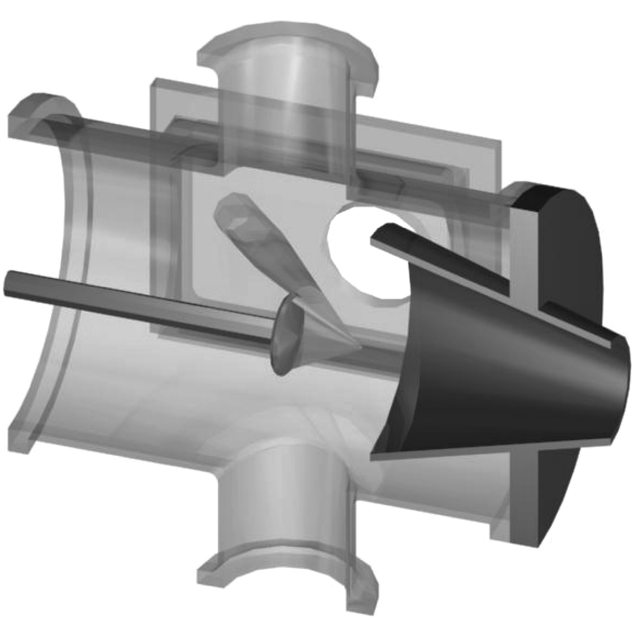


Fig. 9 View of the double Apollo disk model in the IEAv 0.30-m HST test section.

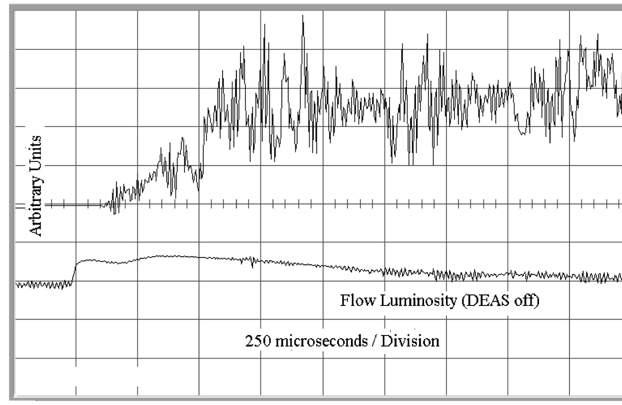


Fig. 10a Typical high-enthalpy impact pressure (top); light sensor 1 (bottom) traces.

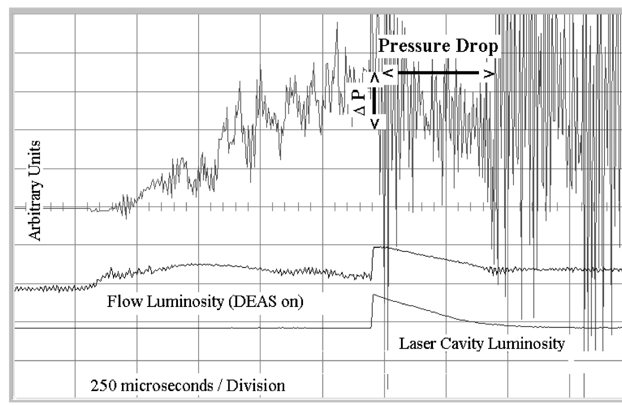


Fig. 10b Typical high-enthalpy impact pressure (top), light sensor 1 (middle), and light sensor 3 (bottom) traces.

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[35] 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. Because 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, 1000 K, and nonequilibrium effects present in the flow could be responsible for the successful laser-induced air ignition at these low static pressures.

Figure 10 shows typical model impact pressure trace (located at stagnation point of the model), for the DEAS off (Fig. 10a) and for the DEAS on (Fig. 10b), 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 caused by 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).[31]

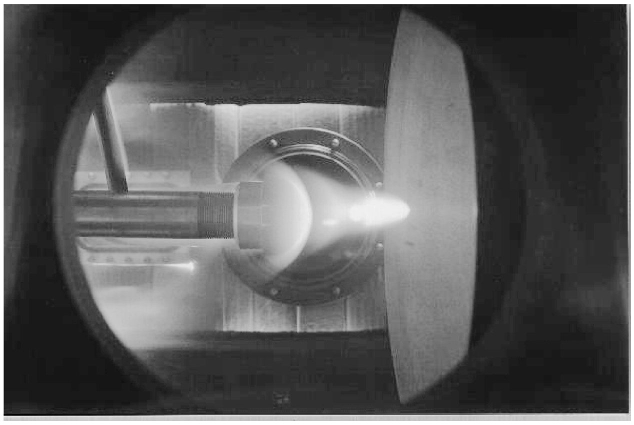


Fig. 11 Open-shutter photograph of the laser-induced air ignition in Mach 6.2 flow and of the strong normal and weak conical shock structures in front of the model.

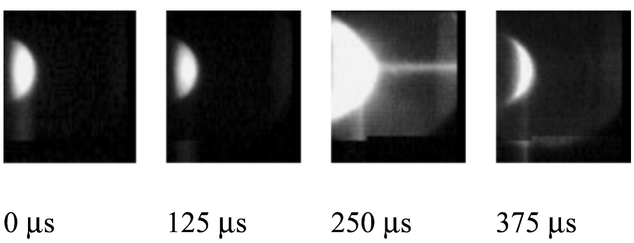


Fig. 12 Time history of the generation and extinction of the laser-supported DEAS in high-enthalpy flow.

Interestingly, 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 might 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.

As stated earlier, 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 11 shows a time-integrated photograph of the laser-induced air breakdown upstream of the model at Mach 6.2 flow conditions (Table 1). Because of 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. Because 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. 11 both the bow shock in front of the model and the parabolic flow structure upstream of it.

The parabolic flow structure seen in Fig. 11 seems to agree with the impact pressure drop observed in Fig. 10 and also with the DEAS mechanism proposed by Myrabo and Raizer.[3] 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. 11 and its schematic view (Fig. 2). This flow structure creates a parabolic-shaped shock wave well ahead of hemisphere.

Additional information on the dynamics of the establishment of the DEAS came with the utilization of a Redlake high-speed camera. Figure 12 shows a sequence of frames taken every 125 μs and an exposure time of 1/24,000 s. From the sequence of frames depicted in Fig. 12, one can see that the bow shock is established over the hemisphere-cylinder model, at 125 μs (only luminosity over the model), until the laser-induced air ignition creates the DEAS, at 250 μs, and the shock wave becomes parabolic. After that, when the air ignition is extinguished, at 375 μs, the bow shock structure is almost reestablished (luminosity over the model and the thermal spot disturbance generated when the pulsed beam from a laser convects with the local flow velocity). This behavior agrees with the trend observed in the high-enthalpy impact pressure trace (Fig. 10), in which the pressure decreases shortly after the establishment of the air breakdown and increases when ignition is extinguished.

Present Results

For the medium-enthalpy conditions present in Table 1 and the conditions shown in Table 2, a more instrumented model shown in Fig. 8 was tested. Surface-pressure measurements can be found in Fig. 13. Such pressure measurements are nondimensionalized 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 with 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 because, as stated earlier, such a configuration can be used as an annular air inlet. The same behavior was observed by Toro and coworkers[10,11] (Fig. 13), using a plasma torch and the same model geometry (energy addition by plasma torch, RPI). Toro et al.[10,11] experiments were performed at Mach number 10 low enthalpy with 770 K stagnation temperature

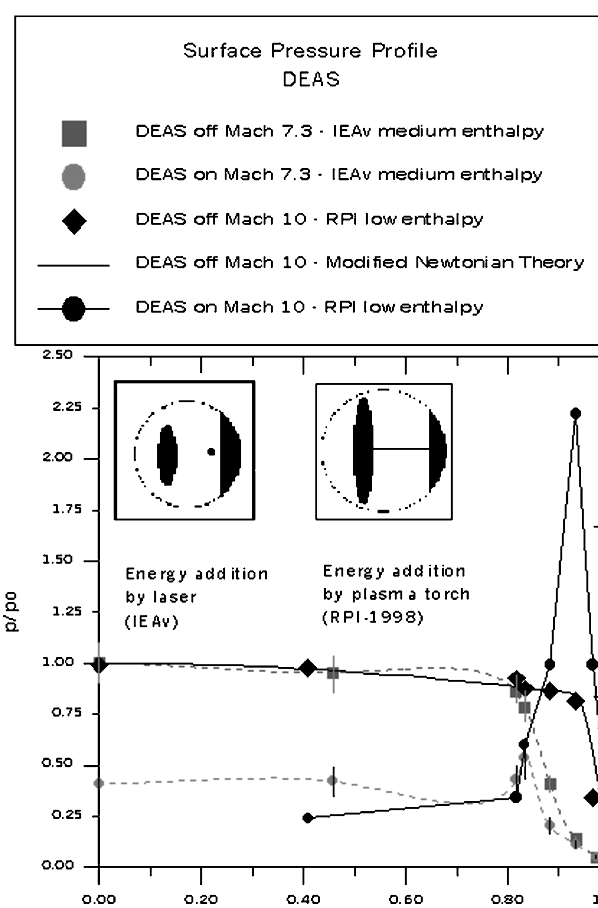


Fig. 13 Surface-pressure distribution over the double Apollo disk model by laser-energy addition (present) and by plasma torch.[10,11]

and 127 kW power added at the tip of the plasma torch. Additional testing might reveal whether increasing the distance from the model front surface to the air ignition location can minimize this pressure increase.

A more detailed history than that depicted in Fig. 12 of the generation and the extinction of the laser-supported DEAS was obtained through the use of the ultra-high-speed Hadland Imacon 790, shown in Fig. 14. 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 μs, resulting in a total of 10 frames each one taken every 10 μs. All 10 frames were recorded onto a single Polaroid 667 film. To facilitate the understanding of the sequence of events, the film was digitized and each individual frame displayed in chronological order. In Fig. 14, 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. 14. 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 four 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 reestablishment of the original bow shock wave.

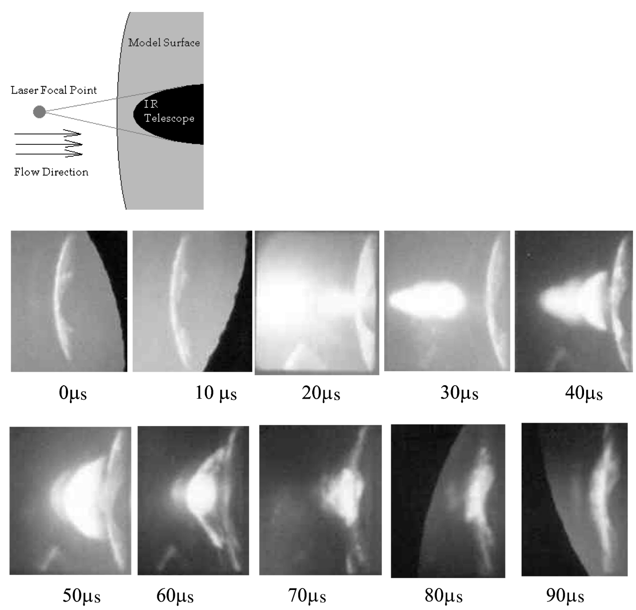


Fig. 14 Time history of the generation and extinction of the laser-supported DEAS in medium-enthalpy flow.

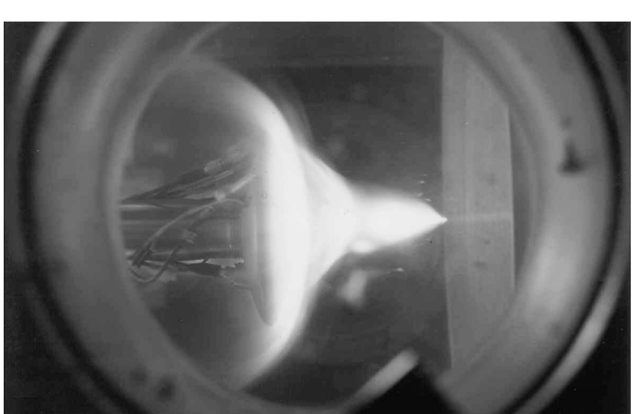


Fig. 15 Open-shutter photograph of the laser-induced air ignition in Mach 7.3 flow and of the strong normal and weak conical shock structures in front of the model.

Figure 15 shows a time-integrated photograph of the laser-induced air breakdown upstream of the model at Mach 7.3 flow conditions (Table 1). Because of stray light, it is possible to see internal details of the test section, the sting mount, the pressure transducer cables, and the nozzle exit. Because 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. 15 both the bow shock in front of the model and the parabolic flow structure upstream of it.

The parabolic flow structure seen in Fig. 15 seems to agree with the DEAS mechanism proposed by Myrabo and Raizer.[3] 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. 15. This flow structure creates a detached parabolic-shaped shock wave well ahead of hemisphere.

Conclusions

Preliminary experiments to demonstrate the laser-supported directed-energy air spike (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 CO_2 transversely excited atmospheric (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. The dynamics of the formation of the parabolic flow structure was revealed through the use of a high-speed camera. Low-enthalpy, ideal air runs were also performed, but the laser-supported air ignition could not be established either consistently or completely.

To further investigate the laser-supported DEAS and to corroborate the promising results herein presented, a new model, fitted with seven pressure transducers, was built. The geometry of the model is the same as the one has being tested by Rensselear Polytechnic Institute 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. More experiments and flow visualization are needed to better understand the phenomenon.

Acknowledgments

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