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Calculation of The Vehicle Drag and Heating Reduction at Hypervelocities with Laser-Induced Air Spike

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ABSTRACT: Scientists at the laboratory of Força Aérea Brasileira (FAB) have demonstrated experimentally that laser-induced "air spikes" (DEAS) may reduce effectively both total vehicle drag and heating at hypervelocities. Now, we apply the Rayleigh flow to directly determine the degree of reduction in vehicle drag and convective heat flux into the airframe of a hypersonic blunt-body when laser energy is added upstream of the flight path. Our numerical findings are in accordance with the physical trends observed in our previous hypersonic laser-induced DEAS experiments.

KEYWORDS: Laser, Flow control, Hypersonic, Rayleigh flow.

INTRODUCTION

Hypersonic technologies now being developed by a few countries, including Brazil, could within two or three decades yield limitless possibilities for air and space travel. In particular, hypersonic flight poses numerous engineering challenges involving many more structural difficulties due to severe heating and dynamic loads, new materials and structures for airframe, predictive models for hypersonic flow, advanced control techniques for hypervelocity flights, new types of airbreathing propulsion systems and proper aerodynamic integration of both airframe and propulsion systems (Heiser and Pratt, 1994).

The Directed-Energy Air Spike (DEAS) is a promising technique for hypersonic flight control, according to which an air spike is induced upstream in relation to the flight path serving to reduce the vehicle drag and to lower heat transfer into the airframe (Myrabo and Raizer, 1994). Air spike production is obtained through many means, including electric arcs (Toro, 1998; Minucci *et al.*, 2000), microwaves (Myrabo and Lewis, 2009) and laser beams (Minucci *et al.*, 2005; Oliveira *et al.*, 2008; Oliveira, 2008; Salvador *et al.*, 2006).

A series of experiments on the concept of hypersonic laser-induced DEAS was performed at the Aerothermodynamics and Hypersonic Laboratory Henry T. Nagamatsu, at Instituto de Estudos Avançados (IEAv), in São José dos Campos, Brazil, conclusively proving that air spikes do work for enhancing flight performance (Minucci *et al.*, 2005; Oliveira *et al.*, 2008; Oliveira, 2008; Salvador *et al.*, 2006). Figure 1 shows the historic hypersonic laser-induced DEAS experiments at the IEAv.

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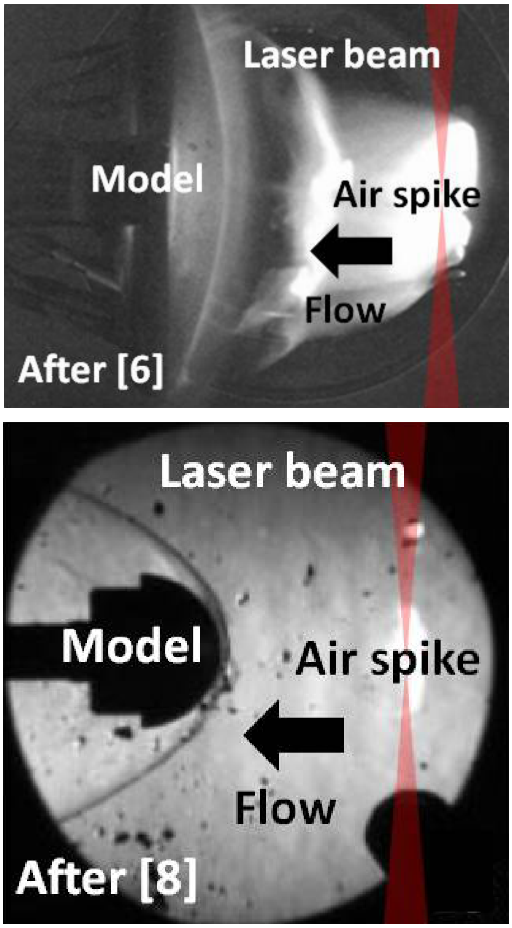

Figure 1. IEAv experiments on hypersonic laser-induced DEAS concept.

Now, we will use the Rayleigh flow to investigate the laser-induced DEAS in hypersonic airflow in a manner that the degree of reduction in vehicle drag and convective heat flux can be easily determined. The methodology is validated by comparison with our previous experimental findings (Minucci *et al.*, 2005; Oliveira *et al.*, 2008; Oliveira, 2008; Salvador *et al.*, 2006).

METHODOLOGY

CONTROL VOLUME AND CONSIDERATIONS

Consider Fig. 2, which illustrates a control volume for one-dimensional flow. Inside this control volume, a laser-supported detonation (LSD) wave and the heating itself cause the hypersonic airflow properties in region 2 to be different than in region 1.

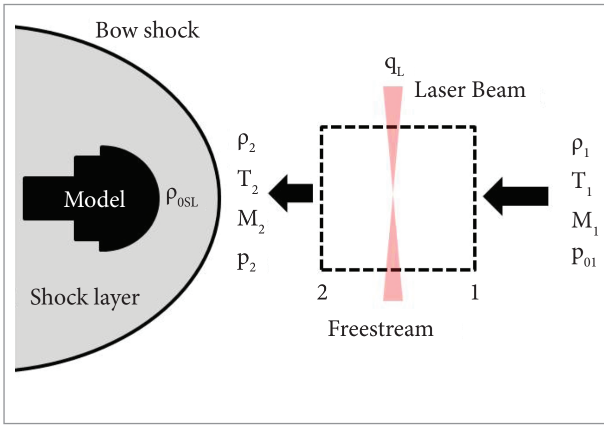

Figure 2. Rectangular control volume for one-dimensional airflow with laser energy addition.

However, the LSD wave is not taken into account for sake of simplicity. Thus, the changes in the one-dimensional flow occurring inside the control volume in Fig. 2 is caused only by the heat added to the hypersonic airflow by the intense beam of laser radiation without the presence of any shock wave.

The governing equations of the hypersonic airflow are continuity, momentum and energy, written as follows (Anderson, 2003):

$$\rho_1 V_1 = \rho_2 V_2 \tag{1}$$

$$p_1 + \rho_1 V_1^2 = p_2 + \rho_2 V_2^2 \tag{2}$$

$$h_1 + \frac{V_1^2}{2} + q_L = h_2 + \frac{V_2^2}{2} \tag{3}$$

They say that mass is conserved (Eq. 1), force equals time rate of change of momentum (Eq. 2), and energy is also conserved (Eq. 3). Note that Eq. 2 neglects body forces and viscous stresses, and Eq. 3 does not include shaft work and work done by viscous stresses, but takes into account the amount of laser energy added by unit of mass, q_L. Since conditions in region 1 are known, for a given q_L these equations, along with the appropriate equations of state and the specific case of a calorically perfect gas, can be analytically solved for conditions in region 2. Although the airflow is hypersonic, we assume that the air is calorically perfect, that is, air with constant specific heats and unchangeable composition. Note that conditions in regions 1 and 2 correspond to freestream conditions of the hypersonic airflow before and after adding the laser energy.

RAYLEIGH FLOW

The analytical relations for the one-dimensional hypersonic flow with laser energy addition can be given as follows (Anderson, 2003):

$$q_L = c_p (T_{02} - T_{01}) \tag{4}$$

$$\frac{p_2}{p_1} = \frac{1 + \gamma M_1^2}{1 + \gamma M_2^2} \tag{5}$$

$$\frac{T_2}{T_1} = \left(\frac{M_2}{M_1}\right)^2 \left(\frac{1+ \gamma M_1^2}{1+ \gamma M_2^2}\right)^2 \tag{6}$$

$$\frac{\rho_2}{\rho_1} = \left(\frac{M_1}{M_2}\right)^2 \left(\frac{1+ \gamma M_2^2}{1+ \gamma M_1^2}\right) \tag{7}$$

$$\frac{T_{02}}{T_{01}} = \frac{T_2}{T_1} \left[\frac{1+ (\gamma-1)M_2^2/2}{1+ (\gamma-1)M_1^2/2}\right] \tag{8}$$

$$\frac{p_{02}}{P_{01}} = \frac{1+ \gamma M_2^2}{1+ \gamma M_1^2} \left[\frac{1+ (\gamma-1) M_2^2/2}{1+ (\gamma-1) M_1^2/2}\right]^{\frac{\gamma}{\gamma-1}} \tag{9}$$

$$S_2 - S_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} \tag{10}$$

They are the basic relations, which are valid for any flow with heat addition or removal, known as Rayleigh flow relations. Table 1 shows the variation in hypersonic flow quantities produced by laser energy addition.

SONIC FLOW CONDITION AND RAYLEIGH TABLE

A methodology for the solution of Rayleigh flow relations is now outlined as follows. All conditions in region 1 are experimentally known. Also, the amount of laser energy added by unit of mass is experimentally estimated *a priori*. Therefore, given q_L, T_{02} can be obtained from Eq. 4. Now, instead of finding the solution of Eq. 8 for M_2 by trial and error, for convenience of calculation we use sonic flow as a reference condition and Rayleigh table for air, which we will explain briefly here. Let M_1=1. Then, the corresponding flow properties are denoted by $p_1 = p^*$, $T_1 = T^*$, $r_1 = r^*$, $p_{01} = p^*_{01}$, and $T_{01} = T^*_{01}$. The flow properties at any other value of M are then obtained by inserting $M_1 = 1$ and $M_2 = M$ into Eqs. 5 to 9, given (Anderson, 2003):

Table 1. Physical trends for Rayleigh flow.

Quantity	Variation for q_L>0 and M_1>1
Mach number	$M_2<M_1$
Velocity	$u_2<u_1$
Temperature	$T_2>T_1$
Pressure	$p_2>p_1$
Total pressure	$p_{02}<p_{01}$
Total temperature	$T_{02}>T_{01}$
Entropy	$s_2-s_1>0$

$$\frac{p_2}{p^*} = \frac{1 + \gamma}{1 + \gamma M} \tag{11}$$

$$\frac{T}{T^*} = M^2 \left(\frac{1 + \gamma}{1 + \gamma M^2}\right)^2 \tag{12}$$

$$\frac{\rho}{\rho^*} = \frac{1}{M^2}\left(\frac{1 + \gamma M^2}{1 + \gamma}\right) \tag{13}$$

$$\frac{T_0}{T^*_0} = \frac{(1 + \gamma) M^2}{(1 + \gamma M^2)^2}\left[2 + (\gamma-1) M^2\right] \tag{14}$$

$$\frac{p_0}{P^*_0} = \frac{1+ \gamma}{1+ \gamma M^2} \left[\frac{2 + (\gamma-1)M^2}{1+ \gamma}\right]^{\frac{\gamma}{\gamma-1}} \tag{15}$$

Equations 11 to 15 are tabulated as a function of M for air in appendix A.3 of Anderson's book (Anderson, 2003). Here, the reference sonic conditions p^*, T^*, ρ^*, p_0^*, and T_0^*, are those in the one-dimensional flow that would exist if enough laser energy is added to achieve Mach 1. The reference sonic conditions achieved when enough laser energy is added to bring the flow to Mach 1 are exactly the same, no matter whether the laser energy is added as q^*_{L1}, downstream of region 1 or as q^*_{L2} downstream of region 2. This is why Eqs. 11 to 15 are simply reference quantities that are fixed for a given airflow with heat addition. With this concept, we can easily obtain M_2. Consequently, any condition in region 2 is calculated directly with Eqs. 5 to 10.

REDUCTION IN DRAG AND HEATING

For the aerodynamic application addressed here, both drag and convective heat flux to the vehicle moving through the hypersonic airflow, before and after adding laser energy upstream of the flight path, should be compared separately. The total drag D and the convective heat flux $\dot{q}$ are proportional to ρV^2 and ρV^3, respectively (Anderson, 2007). Hence:

$$\frac{D_2}{D_1} = \left(\frac{\rho_2}{\rho_1}\right)\left(\frac{T_2}{T_1}\right)\left(\frac{M_2}{M_1}\right)^2 \quad (16)$$

$$\frac{\dot{q}_2}{\dot{q}_1} = \left(\frac{\rho_2}{\rho_1}\right)\left(\frac{T_2}{T_1}\right)^{3/2}\left(\frac{M_2}{M_1}\right)^3 \quad (17)$$

We have used Eqs. 16 and 17 along with the sonic flow condition and Rayleigh tables to discuss theoretically the aerodynamic applicability of laser-induced DEAS to control vehicle drag and heating at hypervelocities. The main advantage of this methodology is simplicity, which allows us to easily compare and contrast the numerical findings with the facts observed in our hypersonic laser-induced DEAS experiments (Minucci *et al.*, 2005; Oliveira *et al.*, 2008; Oliveira, 2008; Salvador *et al.*, 2006).

RESULT AND DISCUSSION

CALCULATION OF DRAG REDUCTION

Table 2 lists our experimental data on laser energy addition in hypersonics (Oliveira, 2008; Salvador *et al.*, 2006), which will be input into the calculations of the reduction in drag and heating. The drag reduction on the blunt body occurs mainly because of the decrease in p_{02} after air spikes are induced by the laser beam upstream in relation to the flight path. A measure is done indirectly by measuring the stagnation pressure in the shock layer behind the bow shock, that is, p_{0SL}. In fact, the magnitude of p_{0SL} decreases after adding laser energy as shown in Table 2. Thus, before calculating drag reduction, we will calculate the reduction in stagnation pressure, and then compare it to the experimental one.

The amount of laser energy added by unit of mass is defined as the ratio between the rate of laser energy, i.e., laser power and mass flow ρVA, in which A is the laser spot size. As a measure of A, we multiply the confocal parameter and the Rayleigh half diameter (assuming a Gaussian laser beam) (Siegman, 1986), as shown in Fig. 3. Note that the laser spot size is not exactly the size of the laser–induced air-spike, which grows rapidly over time. Fortunately, the confocal parameter and the Rayleigh half diameter depend only on the focal length of the lens (200 cm) employed and the laser wavelength (10.6 µm). Hence, the laser spot size can be obtained and, consequently, the laser energy added by unit of mass.

Before adding the laser energy, the hypersonic airflow is isentropic (region 1). Hence, from isentropic airflow properties in appendix A.1 of Anderson's book (Anderson, 2003), for a given M_1 we obtain T_{01}/T_1 and then T_{01} (once T_1 is known beforehand). Eq. 4, assuming that the specific heat capacity at constant pressure of air is constant (1004,5 J/kg.K), gives T_{02}. Now, from the Rayleigh airflow table in appendix A.3 of Anderson's book (Anderson, 2003), for a given M_1 we have p_1/p^*, T_1/T^*, and T_{01}/T_0^*. Let us rewrite T_{02}/T_0^* as $(T_{02}/T_{01})\ (T_{01}/T_0^*)$.

With this and, again, from the Rayleigh airflow table, for a given T_{02}/T_0^* we obtain directly M_2. Now, we calculate the reduction in stagnation pressure, i.e., the ratio between the stagnation pressure after and before laser-induced air spike. The stagnation pressure before adding laser energy is obtained directly from normal shock relations (since M_1 and p_1 are previously known). To obtain the stagnation pressure after adding laser energy, we first need to determine p_2 (see Fig. 2). To do so,

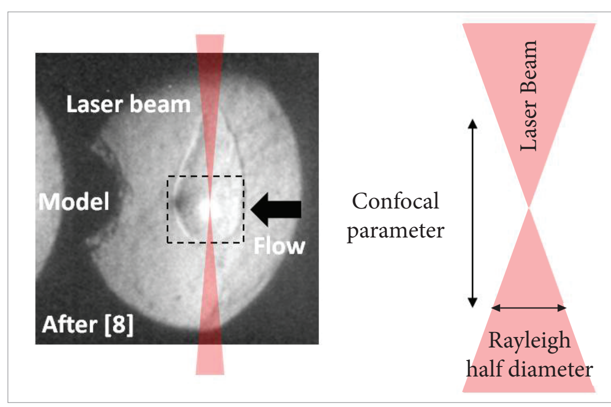

Figure 3. Illustration of laser spot size to estimate the laser energy per unit of mass.

Table 2. IEAv data on laser energy addition in hypersonics.

Enthalpy [unit]	T_1 * [K]	ρ_1 * [kg/m³]	Mach	Speed [km/s]	Laser power [MW]	Stagnation pressure reduction [%]
Low	132	0.1019	6.9	1.6	1.35	31
Low	132	0.1019	6.9	1.6	1.85	43
Low	132	0.1019	6.9	1.6	1.77	48
High	1079	0.0093	5.7	3.4	1.5	54
High	1079	0.0093	5.7	3.4	1.7	45

* Calculated from Hypersonic Shock Tunnel Real Gas (HSTR) software (Oliveira, 2008)

we rewrite p_2 as (p_2/p^*) (p^*/p_1) p_1, in which p_2/p^* and p^*/p_1 are obtained directly from the Rayleigh airflow table for M_2 and M_1 respectively. Also, the stagnation pressure after adding laser energy is obtained directly from normal shock relations (since M_2 and p_2 were obtained previously). Figure 4 shows the reduction in total pressure against laser power for low and high enthalpy flows.

Linear fits represent trends in the data. When there is no laser energy addition, the reduction in total pressure is null. Note that the laser-induced DEAS is more effective to reduce the total pressure as the laser power increases, which is in accordance with Eq. 9. Also, the rate and degree of total pressure reduction is more modest for calculations in comparison with experiments. This is because our methodology assumes no interaction between the bow shock ahead of the blunt body and the LSD wave generated (see Fig. 5), which lowers somehow the strength of the curved bow shock.

The drag reduction is calculated as follows. With the Rayleigh airflow table, for a given M_2 we obtain p_2/p^* and T_2/T^*. Let us rewrite p_2/p_1 and T_2/T_1 as (p_2/p^*) (p^*/p_1) and (T_2/T^*) (T^*/T), respectively. Thus, p_2/p_1 and T_2/T_1 are both obtained. The supersonic solution of the Rayleigh flow implies that both freestream density and temperature will increase while the Mach number will decrease as the laser beam heats the freestream. Finally, with Eq. 16 we calculate D_2/D_1, as shown in Fig. 6. Linear fits represent trends in the data. When there is no laser energy addition, the reduction in drag is null. Calculations show that laser-induced DEAS is more effective to reduce vehicle drag when laser power and flow enthalpy (flow speed) increase. Also, the rate of drag reduction is more modest for low enthalpy. Experimental data on drag reduction still need to be obtained to contrast with the tendencies shown in Fig. 6 in spite of the fact that the reduction in stagnation pressure (see Fig. 4) already suggests that the drag should also decrease with laser energy addition.

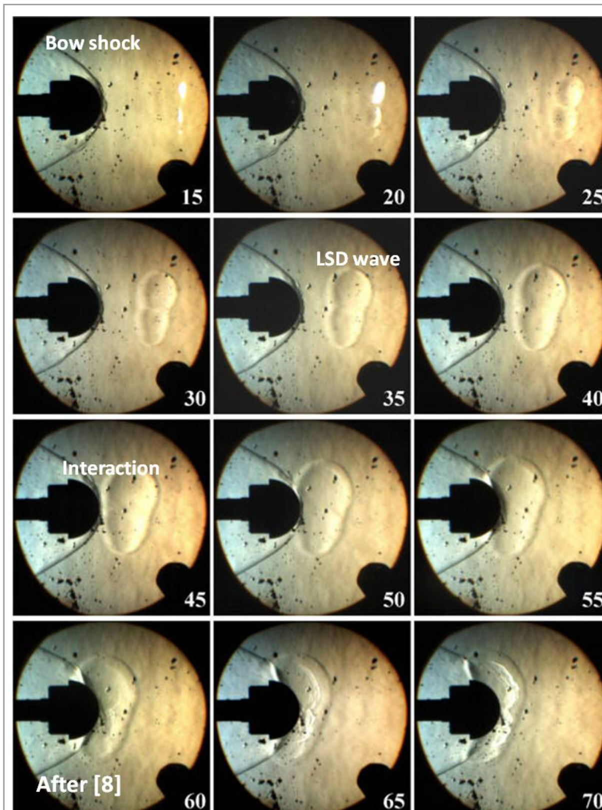

Figure 5. Interaction between bow shock and LSD wave in hypersonic flow.

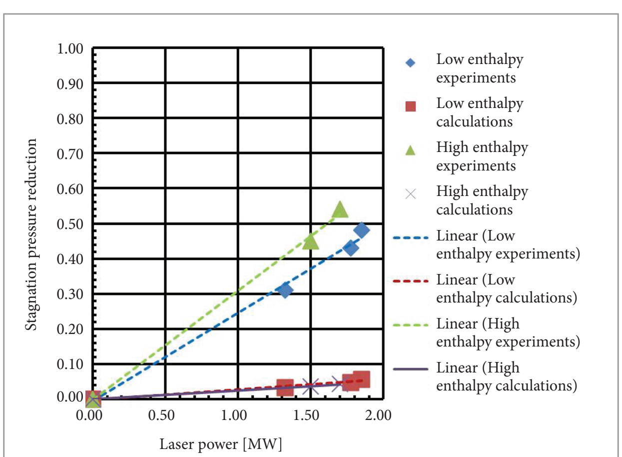

Figure 4. Reduction in stagnation pressure versus laser power for low and high enthalpy flows.

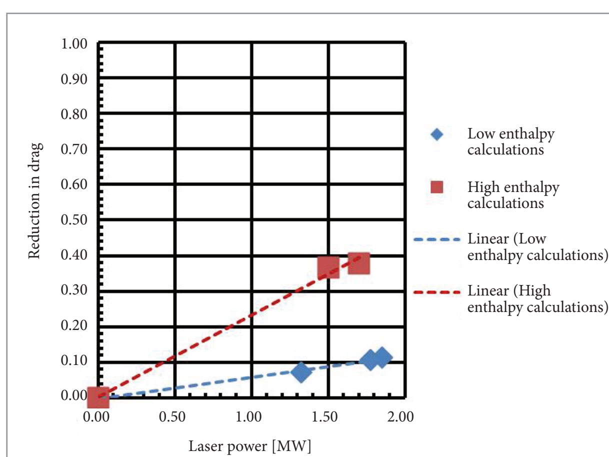

Figure 6. Reduction in vehicle drag versus laser power for low and high enthalpy flows.

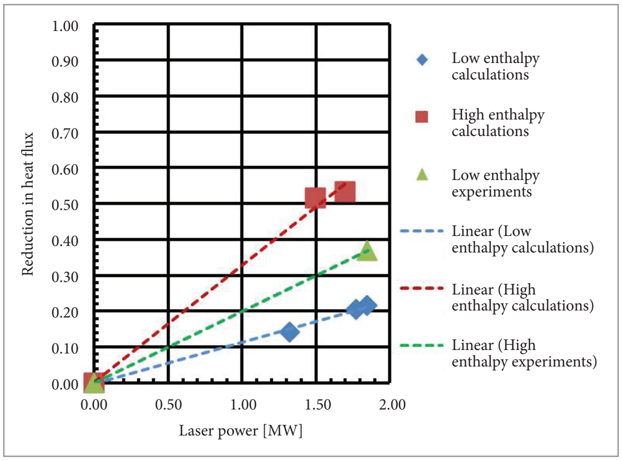

Figure 7. Reduction in heating versus laser power for low and high enthalpy flows.

CALCULATION OF HEAT REDUCTION

The reduction in convective heat flux to the airframe of the blunt, body occurs mainly due to the deceleration of the freestream, as observed in our DEAS experiments. Also, our calculations show a deceleration of the freestream when the laser beam heats the hypersonic flow. The reduction in convective heat flux is calculated as drag reduction, except for the fact that now we use Eq. 17. Figure 7 shows heating reduction as function of laser power with increasing enthalpy. Calculations show that laser-induced DEAS is more effective to reduce heating to the blunt-body airframe as both laser power and flow enthalpy increase. This is because of the term $(M_2/M_1)^3$ in Eq. 17, which contributes effectively to reduce the convective heat flux, that is, increasing q_L forces $M_2 \rightarrow 1$ (chocked flow) and thereby decreasing the ratio. Again, note that the rate and degree of heating reduction is more modest for calculations in comparison with the experiments (Salvador *et al.*, 2006) due to the fact that our methodology neglects the interaction between bow shock and LSD wave.

Our previous hypersonic DEAS experiments revealed that the distance between the blunt body and the laser-induced air spike, as well as the angle of incidence of the laser beam relative to the flow direction, influence the degree of reduction in drag and heating (Oliveira *et al.*, 2008; Salvador *et al.*, 2006). However, our calculations do not consider this fact for the sake of simplicity.

CONCLUSIONS

The hypersonic age of air and space travel will be a reality by 2030. Since 1992, Brazil seeks hypersonic technologies such as scramjet engines, waverider design and advanced techniques for controlling airflow at hypervelocities. We applied the Rayleigh flow relations and sonic flow conditions to determine the degree of reduction in vehicle drag and heating at hypervelocities when laser energy is added to the freestream. Calculations show the same physical trends observed in experiments, clearly indicating that laser-induced air spikes are in fact beneficial to enhance the flight performance of hypersonic vehicles.

REFERENCES

Anderson J.D., 2007, "Introduction to Flight", 6th edition, Science Engineering & Math, pp. 257-263.

Anderson J.D., 2003, "Modern Compressible Flow: With Historical Perspective", 3rd edition, McGraw-Hill, pp. 102-111.

Heiser, W.H. and Pratt, D.T., 1994, "Hypersonic Airbreathing Propulsion", 5th edition, AIAA Education Series, pp. 1-27.

Minucci M.A.S. *et al.*, 2000, "Experimental Investigation of an Electric Arc Simulated "Air-Spike" in Hypersonic Flow", AIAA paper 00-0715, 38th Aerospace Sciences Meeting & Exhibit, Reno.

Minucci M.A.S. *et al.*, 2005, "Laser-Supported Directed-Energy 'Air Spike' in Hypersonic Flow", Journal of Spacecraft and Rockets, Vol. 42, No. 1, pp. 51-57.

Myrabo L.N. and Lewis J., 2009, "Lightcraft Flight Handbook: LTI-20", Apogee Books, pp. 49-66.

Myrabo L.N. and Raizer Y.P., 1994, "Laser Induced Air-spike for Advanced Transatmospheric Vehicles", AIAA paper 94-2451, 25th AIAA Plasmadynamics and Laser Conference, Colorado.

Oliveira A.C., 2008, "Investigação Experimental da Adição de Energia por Laser em Escoamento Hipersônico de Baixa Densidade", PhD Thesis (in Portuguese), INPE, São José dos Campos.

Oliveira A.C. *et al.*, 2008, "Bow Shock Wave Mitigation by Laser-Plasma Energy Addition in Hypersonic Flow", Journal of Spacecraft and Rockets, Vol. 45, No. 5, pp. 921-927.

Salvador I.I. *et al.*, 2006, "Experimental Analysis of Heat Flux to a Blunt Body in Hypersonic Flow with Upstream Laser Energy Deposition - Preliminary Results", 4th International Symposium on Beamed Energy Propulsion, AIP Conference Proceedings, Vol. 830, pp. 163-171.

Siegman A.E., 1986, "Lasers", 1st edition, University Science Books, pp. 663-679.

Toro, P.G.P., 1998, "Experimental Pressure and Heat Transfer Investigation over a Directed-Energy Air Spike Inlet at Flow Mach Number of 10 to 20, Stagnation Temperature of 1000K, with Arc Power up to 127 kW", PhD Thesis, Rensselaer Polytechnic Institute, Troy.