Static and Hypersonic Experimental Analysis of Impulse Generation in Air-breathing Laser-Thermal Propulsion

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ABSTRACT

The present research campaign centered on static and hypersonic experiments performed with a two-dimensional, repetitively-pulsed (RP) laser Lightcraft model. The future application of interest for this basic research endeavor is the laser launch of nano- and micro-satellites (i.e., 1-100 kg payloads) into Low Earth Orbit (LEO), at low-cost and “on-demand.” This research began with an international collaboration on Beamed Energy Propulsion between the United States Air Force and Brazilian Air Force to conduct experiments at the Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonics (HTN-LAH). The laser propulsion (LP) experiments employed the T3 Hypersonic Shock Tunnel (HST), integrated with twin gigawatt pulsed Lumonics 620-TEA CO_2 lasers to produce the required test conditions.

Following an introduction of the pulsed laser thermal propulsion concept and a state-of-the-art review of the topic, the principal physical processes are outlined starting from the onset of the laser pulse and subsequent laser-induced air-breakdown, to the expansion and exhaust of the resulting blast wave.

After installation of the 254 mm wide, 2D Lightcraft model into the T3 tunnel, static LP tests were performed under quiescent (no-flow) conditions at ambient pressures of 0.06, 0.15, 0.3 and 1 bar, using the T3 test-section/dump-tank as a vacuum chamber. Time-dependent surface pressure distributions were measured over the engine thrust-generating surfaces following laser energy deposition; the delivered impulse and momentum coupling coefficients (C_m) were calculated from that pressure data. A Schlieren visualization system (using a high-speed Cordin digital camera) captured the laser breakdown and blast wave expansion process. The 2D model’s C_m performance of 600 to 3000 N/MW was 2.5-5x higher than theoretical projections available in the literature, but indeed in the realm of feasibility for static conditions. Also, these C_m values exceed that for smaller Lightcraft models (98 to 161 mm in diameter), probably due to the more efficient delivery of laser-induced blast wave energy across the 2D model’s larger impulse surface area.

Next, the hypersonic campaign was carried out, subjecting the 2D model to nominal Mach numbers ranging from 6 to 10. Again, time-dependent surface pressure distributions were recorded together with Schlieren movies of the flow field structure

resulting from laser energy deposition. These visualizations of inlet and absorption chamber flowfields, enabled the qualitative analysis of important phenomena impacting laser-propelled hypersonic airbreathing flight. The laser-induced breakdown took an elongated vertically-oriented geometry, occurring off-surface and across the inlet's mid-channel—quite different from the static case in which the energy was deposited very near the shroud under-surface. The shroud under-surface pressure data indicated laser-induced increases of 0.7- 0.9 bar with laser pulse energies of ~170 J, off-shroud induced breakdown condition, and Mach number of 7.

The results of this research corroborate the feasibility of laser powered, airbreathing flight with infinite specific impulse ($I_{sp}=\infty$): i.e., without the need for propellant injection at the laser focus. Additionally, it is shown that further reductions in inlet air working fluid velocity—with attendant increases in static pressure and density—is necessary to generate higher absorption chamber pressure and engine impulse.

Finally, building on lessons learned from the present work, the future research plan is laid out for: a) the present 2D model with full inlet forebody, exploring higher laser pulse energies and multi-pulse phenomena; b) a smaller, redesigned 2D model; c) a 254 mm diameter axisymmetric Lightcraft model; and, d) a laser-electromagnetic accelerator model, designed around a 2-Tesla pulsed electromagnet contracted under the present program.