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Materials response under hypersonic flow conditions probed by multi-modal diagnostics in a benchtop wind tunnel

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Disclaimer

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ABBREVIATED FINAL REPORT

Title: ***Materials response under hypersonic flow conditions probed by multi-modal diagnostics in a benchtop wind tunnel***

PI: Selim Elhadj

Tracking #: 20-ERD-027

Abstract

In this LDRD "Materials response under hypersonic flow conditions probed by multi-modal diagnostics in a benchtop wind tunnel" a peer-reviewed lab-scale hypersonic wind tunnel (WT) was planned to be assembled in-house, along with time and space resolved and related flow and materials diagnostics to derive high quality measurements and the science that is able to inform the development of our modeling and simulation codes for the hypersonic regime. The baseline capability to achieve Mach 3 flow was scheduled to be completed in Q4 2020, in the first year of the LDRD. However due to the COVID-19 delays and travel restrictions starting in March, 2020 this task could not be completed to carry out the materials response studies in-house, or those planned with external partners that were engaged during this LDRD (NASA Langley, NASA Ames, Texas A&M university, and Virginia Tech). Still, using our hypersonic computational fluid simulation codes, many of the hypersonic components have been designed (for Mach 3, 5, and 7) and procured (or in procurement phase), and a new dedicated hypersonic laboratory was facilitized, 2 WT test sections have been manufactured, and a Mach 3 nozzle was 3D printed for prototyping. In parallel, unique materials diagnostics have been tested under static conditions and fully specified and awaiting validation in our partner facilities. Due to the new hypersonic initiative announced in January, 2020 we proposed a related scope increase in hypersonics research requiring energy interactions and new diagnostics well beyond what could be supported by an LDRD ER. A decision was made to end the current LDRD ER and formally propose a new LDRD SI that leverages the current effort, which will be starting in FY21. As a result of the uniqueness of this LDRD work, our early efforts have been encouraged and well received in the hypersonic research community, and is now part of multiple unsolicited internal and external project proposals expected to be funded in the coming years, which is encouraging to make LLNL a leader in experimentally probing extreme physics of local energetics critical to hypersonics.

Mission Impact

DoD and DOE (and DARPA) have interest in determining the response of materials used for high Mach number flight vehicles exposed to reactive flows and the harsh and hostile environment inherent to sustained trans-atmospheric hypersonic controlled flights. NASA and the space industry want to determine re-entry loads to manned spacecraft, spent rockets, or erosion mechanisms to satellites or spacecraft. Therefore, the study of materials response that impact the performance and lifetime of these high velocity vehicles, especially under the most stressed conditions will have an impact on our *Multi-Domain Deterrence* and *Threat Reduction* mission area. We draw on our core competencies in *Lasers and Optical Science and Technology* by developing advanced laser-based diagnostics to analyze flow and materials responses *in situ*, along with *High Performance Computing and Simulation, and Data Science* since our measurements will help extend our simulations and modeling capabilities to the hypersonics regime, which can then be applied to system level assessments. Our Vulnerability and

Hardening assessments are a core competency that need to be extended to the hypersonic regime. This LDRD and the unique data, discovery, and experimental simulation in research hypersonic facility being developed will enable this process. This project will help establish LLNL as a leader in the research of extreme physics of local energetics and materials response critical to hypersonics.

Publications and Presentations

Air Force Research Laboratory Materials and Manufacturing Directorate Presentation (OH), 09/10/2020 (LLNL-PRES-810291)

Note: publications, travel to conferences were greatly impacted by COVID delays and travel restrictions.

FULL TECHNICAL FINAL REPORT

Title: ***Materials response under hypersonic flow conditions probed by multi-modal diagnostics in a benchtop wind tunnel***

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Abstract

Understanding hypersonic environments for trans-atmospheric flight above Mach 5 (i.e., 5 times the speed of sounds) and its impact on materials and vehicle performance is an urgent national priority, which relies on ground test facilities that DOE and DoD need for national security programs and in collaborations with agencies including NASA, the aircraft and space industries, and academia. However, full-scale wind tunnels are extremely resource intensive, with limited optical access (or large standoff), and have thus limited data throughput able to validate computational fluid dynamics (CFD) simulation codes. Therefore, we are reducing the facility scale to focus on measuring key -and most uncertain- local extreme physics phenomena inherent to hypersonics. With time and spatially resolved coupon-level measurements of both the flow and materials response together, we will provide a spectrum of unique data to develop physics models that can more reliably inform scalable system-level simulations in the hypersonic regime. The goal is to accurately predict and understand material physics in extreme environments during prolonged-hypersonic flight conditions with unprecedented extreme *g*, thermal, mechanical stress, and aerothermochemistry loads. To experimentally address the uncertainties surrounding these inherently localized conditions, we are developing a peer-reviewed lab-scale Mach 3-7 wind tunnel (WT) aimed at probing surface features (ex. damage or gaps) on flow and impact on materials response and strength under hypersonic stresses. Diagnostics are being developed in parallel under static conditions, while the wind tunnel is being designed, built, and assembled in-house in a dedicated facility. The baseline Mach 3 capability planned for FY20 and started in the first year of this LDRD ER on October, 2019 could not be completed as planned due to COVID-19 delay that started in March, 2020. This effort was only partially completed. Further, our planned collaborative experimental work with partners (NASA, Texas A&M, Virginia Tech) hypersonics wind tunnels could not be carried due to COVID-19 delay and restrictions on travel. While this LDRD ER effort is ending in its first year, an institutional LDRD strategic Initiative is starting to accommodate the increased scope and diagnostics related to this institutional initiative in experimental hypersonics research. This effort dovetails with multiple existing internal programs and anticipates future external sponsor needs, while providing a steppingstone to harness national facilities, test flights, and establishes deeper collaborations with built-in peer-review already in progress (NASA Langley, NASA AMES, Texas A&M, and others). This represents part of our pivot into hypersonics and will help maintain our lead and relevance going forward in key areas of vehicle development, flight data calibrations, V&H, offense and defense, and simulations V&V to support full-scale vehicle simulation that can reliably assess vulnerabilities, thresholds, and address the upcoming key technical challenges presented by maneuverable hypersonic flight.

Background and Research Objectives

Determining materials response and strength for vehicles in the harsh environment of sustained trans-atmospheric hypersonic flight is challenging because of the need to impose the fully dependent dynamic conditions. These conditions include unprecedented thermal, mechanical loads, along with boundary layer air-surface reactive chemistry subject to dynamic unsteady flowfields, or surface recession. The dynamics become more complex, but no less important, in the presence of off-normal events such as cavities, or damaged features. However, it is also enormously expensive and time consuming to carry out even limited materials response studies in flight tests or national ground test facilities testing in traditional large wind tunnels (WT), even with sub-scale geometries. Worst yet, large facilities with large optical standoff generally lack the close optical access or the possibility to add the diagnostics that could produce the high resolution spatiotemporal datasets needed to validate Computational Fluid Dynamics (CFD) codes being developed internally for the hypersonic regime.

Instead, we believe that the harsh hypersonic environment and related materials response can be understood through investigation of spatially localized effects as the failure points driving a vehicle vulnerability. Damage feature effects could thus be probed on small flat coupons and test articles in a lab-scale facility, rather than in the traditional larger WT typically used for aerodynamic studies, which is not the focus here. The current Wind Tunnel (WT) state-of-the-art approaches for material characterization are limited in close-up diagnostics access, Mach number, are costly[1, 2] or are designed for short-duration combustion runs [3]. The feasibility of small-scale hypersonic wind tunnels has been demonstrated by multiple universities [4-6]. These facilities differ from the proposed design in the scale of integrated capabilities, as they were built for special purposes combustion research [4, 5] or shock-boundary interactions [6], and have shorter operational times (<1 sec) at lower designed Mach numbers (< 3) since their scope of interest is constrained to prevailing applications.

In this work, we address the following two key technical challenges in our inquiry along and list the 3 main research activities below.

1. *What are the local materials responses, strength, failure mechanisms, and failure thresholds when exposed to the experimentally simulated hypersonic environment and surface features , such as damage or gaps?*
2. *Provide accurate time correlated and integrated experimental data at the spatiotemporal scales needed for modeling and simulations (M&S) and CFD code validation being extended to the hypersonic regime.*

The WT assembly with at least a Mach 3 nozzle flow was planned to be completed by Q4 FY20 to carry out the experiments that begin to address the technical challenges noted above. Due to COVID delays that started in March, 2020 (LDRD ER start Oct., 2019), effectively only about 6 months were available for experimental work out of 12 month period of performance. Still, the hypersonic wind tunnel design and some work related to diagnostics development under static conditions were completed as described below. The COVID delay and travel restrictions also affected our planned collaborative R&D with NASA (Langley and Ames), Texas A&M University Dept. of Aerospace Engineering, and Virginia Tech Dept. of Aerospace and Ocean Engineering to test our new diagnostics in realistic hypersonic environment and to begin our experimental research. Therefore the hypersonic wind tunnel and diagnostics development, and experimental research was limited. While this LDRD ER effort is ending in its first year (FY20), an institutional LDRD Strategic Initiative is starting that will leverage this preliminary effort, but which can accommodate the increased scope and diagnostics related to the institutional initiative in hypersonics announced in January, 2020. We expect as a result of this investment to make LLNL a leader in the research of extreme physics of local energetics critical to hypersonics and develop LLNL's hypersonic experimental platform to support LLNL Vulnerability and Hardening (V&H) assessments mission, advanced materials and energetic sources development, and to harness V&H national facilities and flight tests.

Scientific Approach and Accomplishments

I) Wind Tunnel and test platform assembly and development

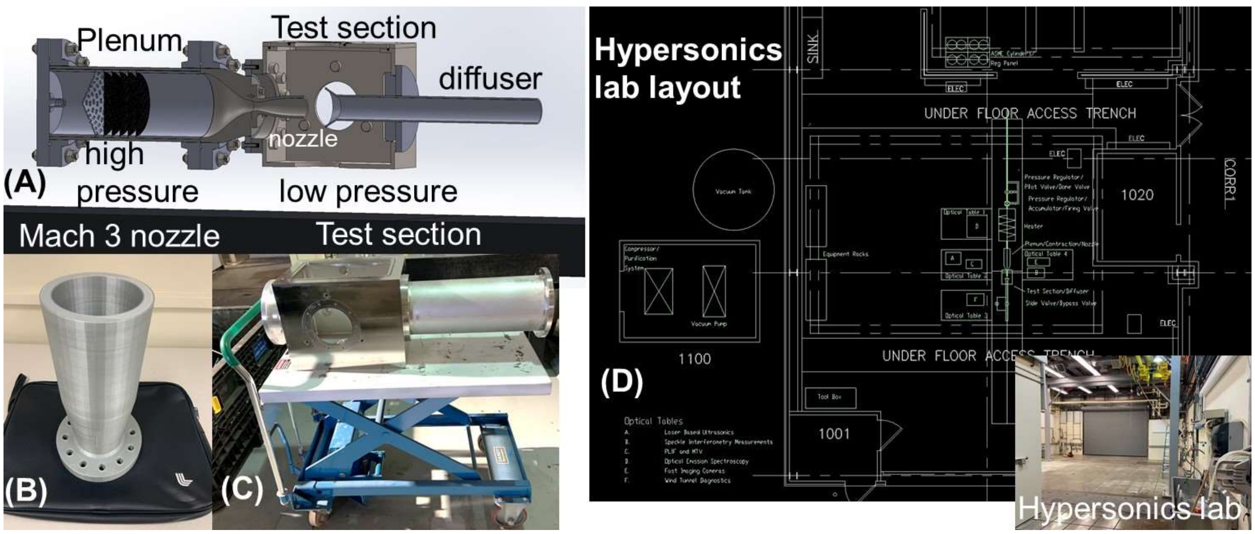

Figure 1. Progress on the in-house hypersonics wind tunnel development that will be integrated with a set of in situ flow and materials diagnostics. (A) from left to right: mechanical design of the plenum, contraction, Mach 3 nozzle, test section, and diffuser (note: diagnostics air source tank, compressor, and vacuum dump tank are not shown). (B) 3D printed Mach 3 converging/Diverging nozzle prototype. (C) test section shown with multiple (top, bottom, sides) line of sight optical apertures for diagnostics optical access. Layout of wind tunnel components in a dedicated facility in B165.

The progress on the Hypersonic Wind Tunnel is illustrated in **Fig. 1**. Two open test sections were assembled, and a dedicated lab space was facilitized to accommodate the layout of the WT components shown (**Fig. 1(D)**). Nozzle designs and mechanical drawings are completed are delivered or in procurement phase (air compressor/filters, 5000 psi pressurized air tanks, vacuum tank, etc.) or in the component fabrication phase (nozzles, plenum, diffuser, etc.). Future plans, will fabricate additional nozzles to achieve Mach 5, and Mach 7 and add an air resistive heating element to prevent air liquification in the expansion of the C/D in the test section. WT instrumentation, WT controls and data acquisition system, stress platform/coupon holder, energetic sources, and stress platform integration will complete the facility R&D capability development as part of future plans concurrently with continued flow and materials diagnostics development below.

II) Diagnostics development, validation, and wind tunnel integration

Diagnostics were developed in parallel with the WT (**Section I**) development. Both materials and flow diagnostics will be tested and those diagnostics that are unproven in a hypersonic WT environment will be validated at partner facilities via contracts and inter-agency agreements to prepare for integration with the WT test section. The range of diagnostics proposed include integrated time and spatially resolved nozzle flow imaging (molecular tagging imaging by planar laser induced fluorescence [12], fast schlieren, and fast shadowgraphy imaging) and materials diagnostics including laser based ultrasonics and laser speckle interferometry. The wind tunnel instrumentation to monitor conditions include pressure gauges and thermocouples. Pitot racks and hot wire anemometry will be used to characterize steady and transient conditions across the core flow from the nozzles to commission the WT and demonstrate uniformity, flow stability, and will be compared to our CFD calculations (**Section IV**). These methods will be ready to be tested and validated with our partners at NASA (AMES and Langley), Texas A&M University (TAMU), and Virginia Tech in the facilities we visited FY19 during this LDRD before COVID travel restrictions.

Only static test of the diagnostics or specification of the equipment needed were performed and results are summarized below. Again, the lack of lab access and continued restrictions have significantly limited the development of these diagnostics.

A key diagnostic in many wind tunnel facilities used to study high speed flow is planar laser induced florescence. This diagnostic operates on either a single photon (PLIF) or two-photon (TALIF) method of exciting transitions in a specific molecule. Targeting various molecules such as NO, OH, O, CO, and many others, this diagnostic captures species concentration as a florescence caused by laser absorption and subsequent emission in a 2D "instantaneous" (~10 ns) profile. By writing patterns into the flow or varying the excitation energy and taking two subsequent images, it is also possible to measure flow parameters such as velocity, temperature, and density, as well as the aforementioned relative concentration.

For the LLNL Wind Tunnel the initial aim was decided to target NO (PLIF) and/or CO (TALIF) for 2D flow visualization efforts. NO is a commonly used seed gas for many other wind tunnel facilities such as NASA Langley [1], Texas A&M [2,3] and various AEDC tests [4,5]. CO is a highly sought-after planar measurement target for V&V efforts in the high-speed ablation modeling community, and for outgassing targets, would allow for flow visualization measurements without a seed gas introduced into the stream. Advantageously, the pump wavelength for the NO/CO measurements are also very near one another in the UV, with NO PLIF at ~225nm and CO TALIF at ~230 nm. There are only a few options among laser classes able to reach these wavelengths, and only dye lasers can do so with narrow enough laser linewidths to excite single transitions and enable temperature measurements.

A system was therefore researched and specified specifically for integration with the wind tunnel. The overall system design is relatively simple, as seen in **Fig. 2**: a dye laser emits a laser beam, which is fed through cylindrically collimating optics to form a laser sheet, which is passed through the experiment of interest. Perpendicular to the sheet, an intensified scientific CMOS camera records the resulting molecular fluorescence, sometimes with a filter to suppress the scattered light from the laser beam, if it is sensitive to those wavelengths. Dye lasers are usually pumped by either Nd:YAG or Eximer lasers, so a combined laser system was necessary. There are 4 companies that produce dye lasers with the appropriate tuning to reach these UV wavelengths: Sirah Lasertechnik, Quantel Laser (recently acquired by Lumibird), Radiant Dyes Laser Acc.

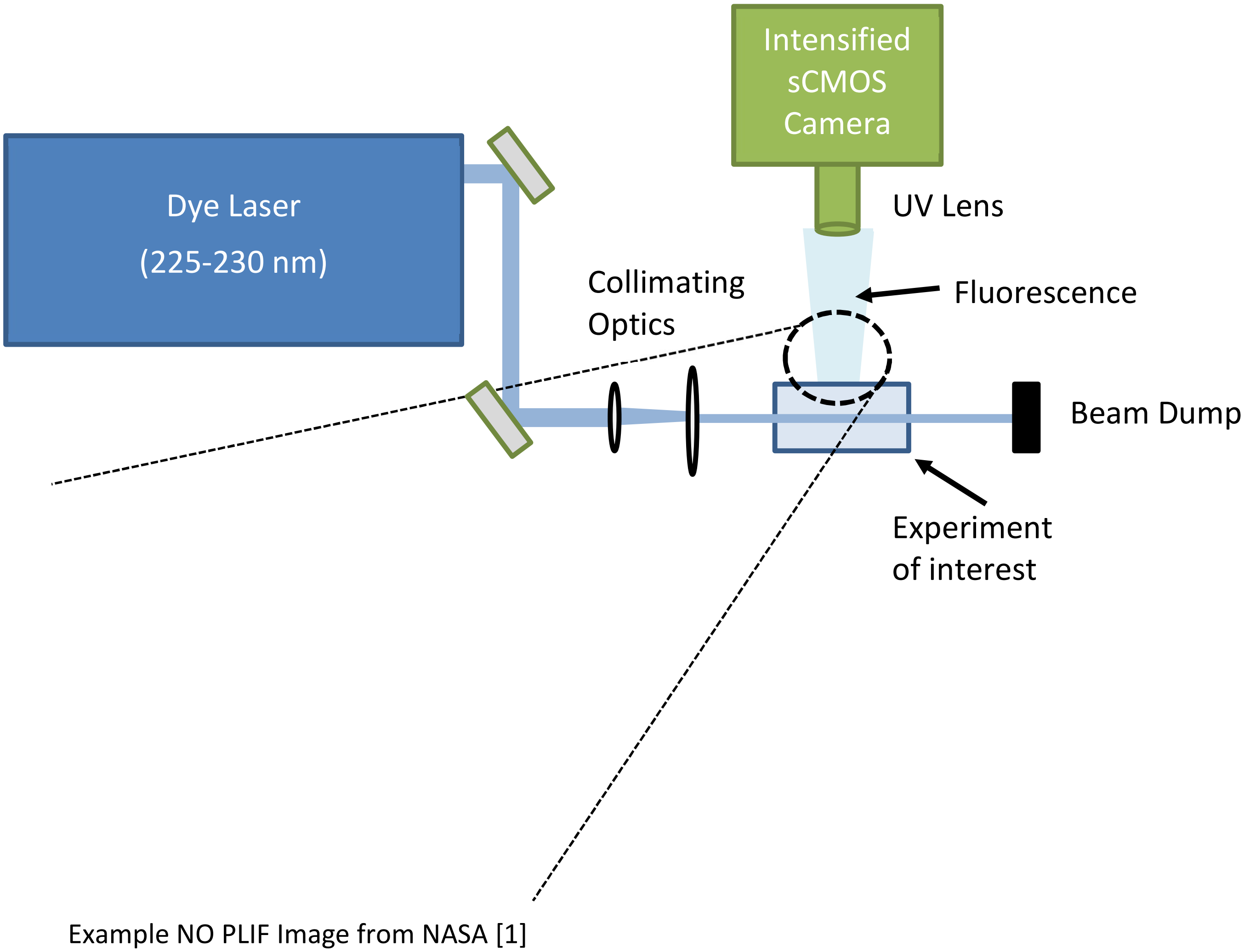

Figure 3. Description and design of a laser based fluorescence imaging of seeded nitrogen oxide as a molecular tag using short pulse UV laser excitation for time resolved imaging using an CMOS camera and optical components shown.

GmbH, and Continuum Lasers (Aquired in 2014 by Amplitude lasers). Continuum Lasers, after the acquisition and move to a new plant, no longer produces new dye lasers although they continue to support existing products in circulation. It was determined that the Radiant Dye laser was the only one suitable for LLNL needs, due to laser energy, portability, and integration with Nd:YAG pump lasers. A similar analysis occurred for intensified cameras and concluded that an Andor iStar sCMOS camera was necessary.

[1] Danehy, P., Ivey, C., Bathel, B., Inman, J., Jones, S., Jiang, N., Webster, M., Lempert, W., Miller, J., Meyer, T., Watkins, A. N., and Goodman, K. Z. Orbiter BLT Flight Experiment Wind Tunnel Simulations: Nearfield Flowfield Imaging and Surface Thermography. Presented at the 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Orlando, Florida, 2010.

[2] Sánchez-González, R., and North, S. W. Chapter 18 - Nitric Oxide Laser-Induced Fluorescence Imaging Methods and Their Application to Study High-Speed Flows. In *Frontiers and Advances in Molecular Spectroscopy* (J. Laane, ed.), Elsevier, 2018, pp. 599–630.

[3] Sánchez-González, R., Srinivasan, R., Bowersox, R. D. W., and North, S. W. “Simultaneous Velocity and Temperature Measurements in Gaseous Flow Fields Using the VENOM Technique.” *Optics Letters*, Vol. 36, No. 2, 2011, pp. 196–198. https://doi.org/10.1364/OL.36.000196.

[4] Havener, G., and Smith, M. Holographic and PLIF Measurements of Free-Flight Hypervelocity Flowsin the AEDC Range G Facility. Presented at the 28th Joint Propulsion Conference and Exhibit, Nashville,TN,U.S.A., 1992.

[5] Ruyten, W., Smith, M., and Price, L. Status of Laser-Induced Fluorescence and Planar Laser-Induced Fluorescence Measurements in the AEDC HEAT-H2 Arc Heater Facility. Presented at the 30th Thermophysics Conference, San Diego,CA,U.S.A., 1995.

The fast shadowgraphy air density flow measurements with MHz imaging capability and tested in a low pressure chamber using laser induced air breakdown to generate a shockwave blast traveling at supersonic speeds. The ability to image in air density at low pressure is very challenging at 1/100th atmospheric pressure (corresponding to high altitude flight conditions) but was demonstrated. In **Figure 3**, a single frame of the shock propagating is shown using 10 MHz illumination pulses synched with 10 MHz camera capture rate (10 million frames per second).

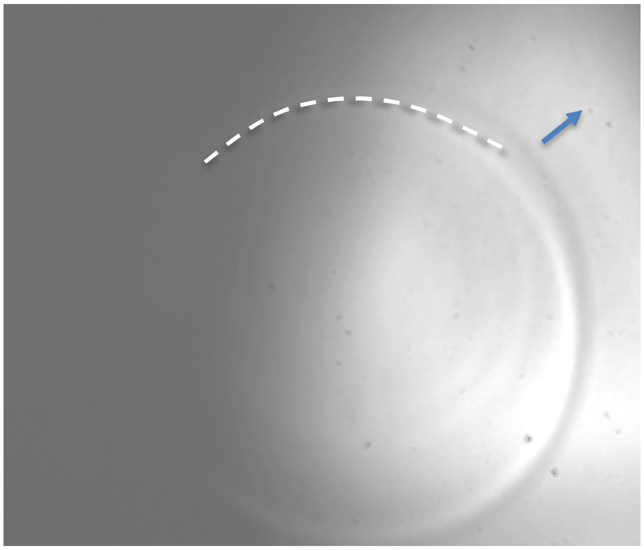

Figure 2. Supersonic shockwave blast imaged at near vacuum ~ 10 Torr in air. Partial contour and shock propagationshown for clarity.

Laser-based ultrasound (LBU) is a non-contact and remote method of ultrasonic materials measurements known to be highly effective for measuring mechanical properties of the material, component dimensions, and characterizing subsurface defects. We designed and constructed an LBU system for this LDRD, which includes a nanosecond pulsed laser to excite ultrasonic waves in a sample coupon while a nearly coincident photorefractive interferometer detects surface normal displacements at the sample surface. Although the photorefractive interferometer is a technique that is a very insensitive to sample surface roughness, a risk for this project is to be insensitive to environment changes and vibrations typical in a noise hypersonic flow environment (such as the wind tunnel test section), while still being sensitive enough detect the sample surface displacements.

After a literature review and engaging with a number of companies, we identified a double differential fiber-optic Sagnac interferometer system from LuxSonics, Inc. as a potential solution. This type of interferometer uses two phase-delayed laser beams that are reflected from the sample surface, and the interference between these two beams provide surface displacement measurements that will be, in principle, "*stable to environmental vibrations and temperature fluctuations*" [1]. This technique also benefits from being insensitive to sample surface roughness, similar to the photorefractive interferometer. We have procured and received a LuxSonics, Inc. double differential fiber-optic Sagnac interferometer, and plan to conduct high resolution LBU scans on relevant test samples of interest. Recent studies have shown the ability for LBU, with a Sagnac interferometer, to characterize the evolution of porosity in fiber-reinforced composites to help define a strength model of materials in such environment as hypersonic flight conditions [2]. This measurement has never been performed in a hypersonics environment and could be leveraged in much larger facilities fi successful.

Figure 4. Double differential fiber-optic Sagnac interferometer from LuxSonics, Inc.

[1] I. Pelivanov, T. Buma, J. Xia, C.-W. Wei, and M. O'Donnell, "NDT of fiber-reinforced composites with a new fiber-optic pump–probe laser-ultrasound system," Photoacoustics, vol. 2, no. 2, pp. 63–74, Jun. 2014.

[2] I. Pelivanov and M. O'Donnell, "Imaging of porosity in fiber-reinforced composites with a fiber-optic pump–probe laser-ultrasound system," Composites Part A: Applied Science and Manufacturing, vol. 79, pp. 43–51, Dec. 2015.

In addition to LBU materials diagnostic above, we plan a series of compact experiments to evaluate the applicability of Laser Speckle Interferometry (LSI) to measure in situ in a wind tunnel environment the in-plane and out of plane surface displacement without needing sample prep (as in DIC for ex.). The measurement could also in principle measure the recession during local energy interactions and formation of damage. The approach will involve a laser illumination of a test specimen or coupon surface in situ under varying wind tunnel conditions and stresses applied (mechanical, heat, …). Measurements of the speckle pattern over imaging frames is then analyzed to get surface time resolved surface displacement and kHz vibration as well. The goal of these experiments is to characterize the stability of the speckle pattern – and the suitability of these types of techniques in hypersonic environments– under hydrostatic and dynamic pressure found in hypersonic airflow conditions of hypersonics wind tunnel. Specifically, the optical setup involves the use of laser speckle in at least two different configurations: 1) an in-plane method to determine in-plane displacements with very high sensitivity and 2) an out-of-plane configuration designed to maximize sensitivity to surface tilt. The first configuration is most useful for determining in-plane strain resulting from flow-induced shear stresses and/or thermal stresses while the second can be used to visualize the nodal/anti-nodal distribution of a vibrating surface as well as quasi-static surface tilting behavior. The surface tilt data is useful for determining curvature – critical information when determining stresses in plates and thin shell assemblies. All aforementioned methods are full-field, non-contact and high-sensitivity provided, of course, that the hypersonic environment permits the formation of a speckle pattern with sufficient temporal stability. The method involves the simple illumination of a test sample by a diverging laser beam and subsequent imaging via grayscale machine vision camera. To this end, the laser and camera is mounted outside the chamber. The emitted beam from the laser is made to enter a microscope objective of sufficient magnification to cause the resulting cone of light to encompass the area of interest on the sample surface. Images will be collected under varying velocities and pressures and post-processed. No special vibration isolation mounting will be necessary. The concept could only be tested briefly with a preliminarily tested on a large turbine blade manually deformed by touch and imaged with a camera using green laser illumination (data not shown). Similarly as the LBU measurement, the LSI approach, to the best of our knowledge, has never been attempted in a hypersonics environment and could be leveraged in much larger facilities if successful producing new methods for hypersonics materials research.

III) Simulations for WT design, experimental design, and modeling

For this LDRD we implemented a modeling capability to simulate hypersonic flows with options for steady, unsteady, laminar, turbulent, boundary layer transition, two temperature, thermal-chemical nonequilibrium, radiation, and plasma. In such flows that exhibit high temperature, air dissociation is required either using 5 or 11 species. We are using two codes, Stanford open source code SU2 and a commercial code starccm+. Both codes are highly scalable and can handle complex geometries. A visiting Stanford graduate student that has been funded for the next two years, through an internal grant, to improve SU2 hypersonic flow modeling capabilities and provided flow simulation support for the Wind Tunnel experimental design and testing. So far, our modeling capabilities has been applied in the design of the wind tunnel and will be used in understanding the flow interaction with either the coupon or a test article in the open test section of the wind tunnel. Also, we have experience applying this flow modeling capability to generic geometries and full-scale complex flying vehicles at hypersonic speed with inclusion of surface flaws or cavities and air dissociation.

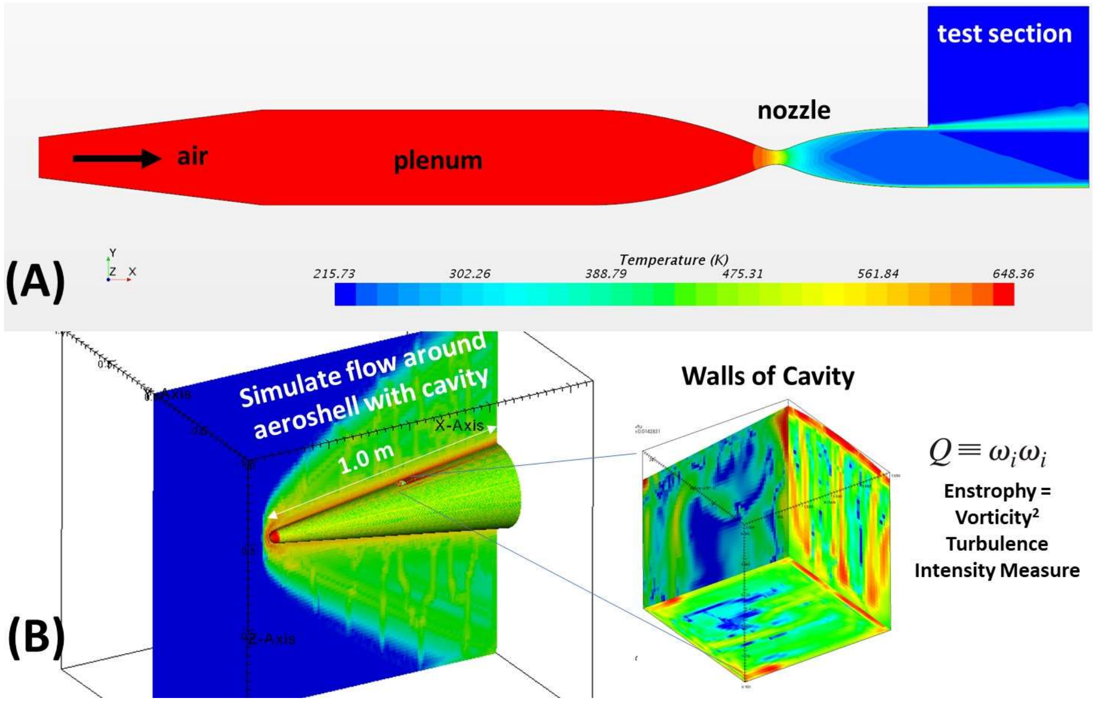

Figure 5. (A) Numerical CFD simulations from LDRD team member Kambiz Salari of flow and temperature through LLNL wind tunnel components includes flow in diffuser, plenum, axi-symmetric nozzle, test section with test platform in an open-jet configuration. (B) LLNL MARGOT LES/DNS for local-Scale cavity analysis providing unique high-to-full resolution simulations of turbulent drag and heating events on cavity features in the hypersonic regime (courtesy Greg Burton, LLNL)

In this proposed research, we will leverage our substantial expertise gained in the high-resolution computational study of hypersonic flows, with our development of MARGOT, a multiphysics, massively-parallel MPI-based DNS/LES hypersonics code currently working the NNSA and DoD mission spaces (**Fig. 5**). With MARGOT we are now conducting nearly fully-resolved (i.e. model-free) simulations of hypersonic flows around small-sized (<0.05m^3) damage features to inform system level performance and survivability studies. To perform effective validation of the simulations, several test cases addressing different aspects of aerothermodynamics interactions with materials will be included in the project plan: experimentally simulated low-to-high enthalpy effects in the wind tunnel (or in our partner miniarcjet facility at NASA). and low-to-high Mach number flow interactions with bulk heated flat samples with a range of geometries and engineered surface features. Reactive-flow conditions including, mass transport, speciation, dissociation, mixing, pressure and temperature will be created and measured to validate chemical kinetic models of the gas-gas and solid-gas phase reactions during the erosion process as a function of Mach number, atmosphere, test configuration, and mechanical stresses. Simulation capabilities are therefore now ready to continue supporting the development of the wind tunnel test and materials response to damage and other type of hypersonics stress.

IV) Materials Strength, failure modes, and failure thresholds studies

Failure thresholds and failure modes of materials, such as reinforced carbon-carbon, include outgassing and sub-surface cracks evolution when exposed to the combined stress and heat loads (up to 1700C) during hypersonic flight, in particular at leading edges [8]. The proposed laser based ultrasonics[16] (LBU) will attempt to capture this process -for the first time- *in situ* in the wind tunnel on flats and in the presence of cavities. Ablation and local surface recession rates and boundary layer reaction chemistry will be captured by a combination of Speckle interferometry and PLIF measurements, respectively. Strain and stress states at failure (Speckle) will also be captured *in situ* for the first time in the wind tunnel and by applying simulated stresses using the wind tunnel stress platform. Due to the lack of access to partners hypersonic facilities for experiments due to COVID travel restrictions and delays, we were not able to carry out our planned materials experiments in this first and only year of the LDRD effort.

Mission Impact

Describe the significance of this research to Laboratory missions and its likely impact on programs, including new capabilities, new directions, and new work or staff brought to the Laboratory. Also describe the relevance of the results with regard to NNSA, DOE, and other national missions. In addition, for the full technical report, you can submit an expanded description of your project's mission impact, which could include OUO, proprietary, or export-controlled information, as the full technical report will not be publicly release.

DoD and DOE (and DARPA) have interest in determining the response of materials used for high Mach number flight vehicles exposed to reactive flows and the harsh and hostile environment inherent to sustained trans-atmospheric hypersonic controlled flights. NASA and the space industry want to determine re-entry loads to manned spacecraft, spent rockets, or erosion mechanisms to satellites or spacecraft. Therefore, the study of materials response that impact the performance and lifetime of these high velocity vehicles, especially under the most stressed conditions will have an impact on our *Multi-Domain Deterrence* and *Threat Reduction* mission area. We draw on our core competencies in *Lasers and Optical Science and Technology* by developing advanced laser-based diagnostics to analyze flow and materials responses *in situ*, along with *High Performance Computing and Simulation, and Data Science* since our measurements will help extend our simulations and modeling capabilities to the hypersonics regime, which can then be applied to system level assessments. Our Vulnerability and Hardening assessments are a core competency that need to be extended to the hypersonic regime, this LDRD and the unique data, discovery, and experimental simulation in our unique hypersonic wind tunnel facility will help in this process. When successful, this project will help establish LLNL as a leader in the research of extreme physics of local energetics and materials response critical to hypersonics.

Conclusion

While this LDRD ER effort is ending in its first year, an institutional LDRD strategic Initiative was announced in January, 2020. An increased scope involving energy interactions studies and new diagnostics needed to support this research was proposed by the same PI. The new scope and diagnostics were well beyond the ability of the current LDRD ER to, so we proposed to end this LDRD ER in its first year and continue with an LDRD SI that leverages the investments made in the LDRD ER. After a proposal, this effort will be supported starting in FY21 through FY23. During our first year of LDRD ER the new effort we undertook in the LDRD ER and the unique R&D capability it represents in materials research was noticed externally and has been part of multiple DoD efforts (4). At least one of them was endorsed for start expected in 1 or 2 years. We expect many internal and external partners will become partner with our unique facility for hypersonics research for years to come, and will make us a premier institution in the validation and development of modeling and simulation codes in the hypersonic regime and extreme physics related to that environment.

What happens next? Describe the way forward for this body of work, such as the potential for transfer to industry, future collaborations, or support for continued research from other agencies or private industry.

Publications and Presentations

Air Force Research Laboratory Materials and Manufacturing Directorate Presentation (OH), 09/10/2020 (LLNL-PRES-810291)

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