
CONSTRUCTION AND TESTING OF A TABLE-TOP SHOCK TUNNEL

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14. ABSTRACT A new "table-top shock tunnel (TTST)" has been constructed and is intended to allow rapid and low-cost measurements of shock-layer chemistry and material response in well-characterized high-velocity flows. The TTST is based on the production of pulsed hypersonic molecular beams by laser detonation in a conical nozzle. In addition to providing fundamental data for the development of models, the production of controlled shock layers above ablating and non-ablating surfaces and the measurement of their phenomenology provide a means to validate new models. Furthermore, material response can be tested in realistic environments and aid in the development of materials for hypersonics applications. Initial characterization of the TTST has been carried out by studying the ablation phenomenology of a Kapton H polyimide surface exposed to a hypersonic O/O2 beam at various distances from the nozzle throat and comparing the experimental observations with the results of DSMC calculations.					
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TABLE OF CONTENTS

Section	Page
1. SUMMARY	1
2. INTRODUCTION	2
3. METHODS, ASSUMPTION, AND PROCEDURES	3
4. RESULTS AND DISCUSSION	4
5. CONCLUSIONS.....	10
REFERENCES	11
APPENDIX A: DETAILS OF CONSTRUCTION, PERSONNEL SUPPORTED, AND TIMELINE.....	13

LIST OF FIGURES

Figure	Page
1. Flow Regimes Relevant to Hypersonic Ablation.....	2
2. Diagram of the Table-Top-Shock Tunnel.....	3
3. Velocity Distributions of Components of Two Hypersonic Molecular Beams.....	4
4. SEM Images of Kapton H Surfaces Exposed at Various Distances	5
5. AFM Images of Kapton H Sample Exposed to the Hypersonic O/O ₂ Beam.....	6
6. DSMC Simulation Domain.....	7
7. Target Face Split into Three Radial Regions, Labeled Center , Mid , and Edge in Fig. 10	7
8. DSMC Simulation of the Temperature of the Flow over the 25 mm Diameter Object at 40 cm from the Nozzle Throat.....	8
9. DSMC Results Showing the Relationship Between O-atom Velocity and Impingement Angle onto the Surface (with respect to the surface normal) for the Centers of Samples Exposed at 20, 35, and 50 cm from the Nozzle Throat	8
10. DSMC Results Showing the Relationship Between Particle Velocity and Impingement Angle onto the Surface (with respect to the surface normal) for a Sample at 35 cm from the Nozzle Throat, at the Sample Center, Mid, and Edge	9
11. Photograph of the Operational TTST System.....	13

LIST OF TABLES

Table	Page
1. DSMC Simulation Conditions for this Study	6

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1. SUMMARY

We have attempted to fill a gap in hypersonic testing with the development of a new apparatus for investigating shock layer physics under relevant conditions. The basic idea is that a high-velocity pulsed molecular beam, when targeted at a small blunt object, can generate a hypersonic shock layer that exhibits relevant dissociation physics and ablation chemistry. Unlike large shock-tunnel facilities, the free stream is well characterized, and the beam (and therefore the shock layer) can be generated (pulsed) 2-3 times per second for hours or even days with repeatable conditions, providing a practical laboratory environment for detailed investigations of shock layer chemistry and physics, as well as ablation phenomena. Despite its relatively small size, the new instrument can be used for rapid acquisition of high-fidelity data on shock layer chemistry that will provide definitive validation of emerging models. This facility fits in a common laboratory space, and the vacuum chamber (including the hypersonic beam, target, and beam diagnostics) occupies a footprint smaller than a typical laser table. Thus, this instrument is referred to as a “Table-Top Shock Tunnel” or “TTST”. The hypersonic beam is based on the laser-detonation source [1-4] that has been used in studies of hyperthermal gas-phase and gas-surface scattering dynamics, mainly related to atomic-oxygen effects on materials in low Earth orbit. This beam can create reproducible and intense pulses of gas with nominal velocities of 6-9 km s⁻¹ at repetition rates of 2-3 Hz.

The transformative novelty of the TTST is threefold. (1) A well characterized gas or gas mixture (in terms of velocity distribution, mole ratio, and chemical state) can be directed at a target. (2) The high repetition rate and reproducibility of hypersonic pulses of sufficient intensity to form a shock above a target allows for high quality spectroscopic data to be obtained with standard diagnostic tools, such as optical emission, coherent anti-Stokes Raman spectroscopy (CARS) or, possibly, laser induced fluorescence (LIF). (3) The target may be ablating or non-ablating; in the case of an ablating material, the sample may be heated to high temperatures, allowing for the investigation of the boundary layer above an ablating material as well as studies of the ablated surface. This experimental setup is not appropriate to study fluid dynamic phenomena such as high Reynolds number flow (transition and turbulence), shock-boundary layer interactions, separated flow, and it cannot exactly reproduce free-stream flight conditions. Nevertheless, no ground-based facility can capture all flight-relevant processes and provide a feasible means for optical measurements. The TTST concept focuses specifically on producing data for nonequilibrium dissociation, vibrational and rotational populations, and gas-surface interactions. It is this focus that may enable the TTST to obtain high-quality fundamental data for relevant conditions that no other existing facility can.

A DURIP equipment grant (FA9550-19-1-0112) provided the funds for the hardware to construct a new apparatus for investigating shock layer physics under relevant hypersonic conditions. Additional funds were used from the PI's startup award when he relocated to the University of Colorado. The funds from the AFRL grant were vital to the actual construction and testing of the new TTST, which is the subject of this report. It should be noted that the evaluation of the new facility relied heavily on the direct simulation Monte Carlo (DSMC) calculations that were conducted by Prof. Thomas Schwartztruber's group at the University of Minnesota, who were supported by a companion AFRL grant (FA9453-20-1-0012). Thus, relevant results from the DSMC calculations that aid in the interpretation of the test data are also reported here.

2. INTRODUCTION

Hypersonic ablation of a thermal protection system (TPS) material in air involves four coupled flow regimes [5], as depicted in Fig. 1. These include (1) shock-induced dissociation of air molecules, (2) air chemistry involving gaseous ablation products (e.g., CO and CO₂ for a carbon-based TPSs), (3) diffusion of reactive species to the TPS surface, and (4) local gas-surface chemical reactions. Current experimental measurements of the shock and boundary layers (subsequently referred to collectively as the “shock layer” in this paper) are difficult and expensive to perform, and ground-based experiments simply cannot reproduce the wide range of potential flight conditions. Therefore, accurate predictive models are required for use in computational fluid dynamics simulations. The most widely used vibrational energy model is the Millikan-White model [6], and the most widely used dissociation model is the Park T_{Tv} model [7]. Both of these models are empirical and based on relatively few experimental data sets. Their accuracy outside of the limited experimental conditions is uncertain, and this uncertainty directly affects the prediction of all other coupled processes shown in Fig. 1. To reduce this uncertainty, a significant amount of research has been performed using computational chemistry [8-13]. These first-principles, predictive simulations and models have been shown to reproduce the limited experimental results [6,14-16] used to construct the empirical Millikan-White and Park T_{Tv} models. However, the first-principles calculations differ significantly from these empirical models for other hypersonic conditions where no experimental data exist [10,11,12]. For this reason, new optical diagnostic data measured under relevant hypersonic flow conditions are needed to validate these new models. Such experiments are extremely challenging and expensive, and no such data sets, sufficient to validate new models, have been generated to date.

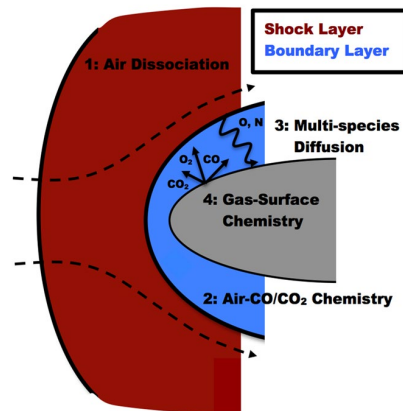


Figure 1. Flow Regimes Relevant to Hypersonic Ablation (Not to scale.)

A key challenge of testing in ground-based facilities is that true hypersonic conditions can only be sustained for short test times (microseconds to milliseconds). Collecting optical diagnostic data, for example, during such short timescales in a high-temperature gas is extremely difficult (low signal to noise). Furthermore, high-enthalpy facilities tend to be large facilities where only a few tests can be performed per day and precise repeatability between tests is difficult. Examples of such facilities are located at CUBRC [17], the University of Queensland [18], NASA Ames (EAST facility) [19], and Stanford University [16]. Alternatively, lower-enthalpy facilities have longer test times, and therefore optical measurements can be made more easily. However, the relevant thermochemical nonequilibrium processes in the shock layer are no longer present. Such

facilities include those at the University of Canberra [20], Caltech (formerly located at the University of Illinois) [21], and Ohio State University [22].

3. METHODS, ASSUMPTIONS, AND PROCEDURES

A diagram of the TTST facility is shown in Fig. 2. The heart of the TTST is a laser-detonation hypersonic beam source [1-4]. A pulsed valve is used to inject gas at high pressure (>550 psi) into the 1 mm diameter throat of a conical nozzle. After the gas expands into the nozzle, a 7-12 Joule per pulse CO₂ TEA laser is fired, and the light is focused down into the nozzle where it induces a breakdown and heats the resulting plasma to 40,000 – 50,000 K in the confined space near the nozzle throat. The detonation wave that is produced dissociates and accelerates the gas, and a neutral pulse emerges from the nozzle, containing partially dissociated gas, with the extent of dissociation depending on various operating parameters of the source. The pulse has a velocity distribution of ~ 2000 m s⁻¹ full width at half maximum (fwhm), and the nominal velocity can be varied from about 6 to 9 km s⁻¹. Beams may be produced with precursor gases, O₂, N₂, Ar, CO₂, and N₂O. Mixtures of these gases may also be used, and one can imagine additional precursor gases. For diatomic and polyatomic precursor gases, there is considerable dissociation in the nozzle. The repetition rate of the source is currently limited to 2-3 Hz by pumping constraints. The hypersonic beam source is attached to a main “shock chamber,” where a target object may be placed. The base pressure of this chamber is $\sim 10^{-7}$ Torr. Optical beams for future Schlieren and laser-based diagnostics will pass through the main shock chamber. The position of the object is variable, with nozzle-throat-to-sample distances of 15-65 cm. The allowable sample area increases with distance, but a sample diameter of 25 mm is possible at all distances. The pulse width of the beam is determined under the assumption of a point source at the nozzle

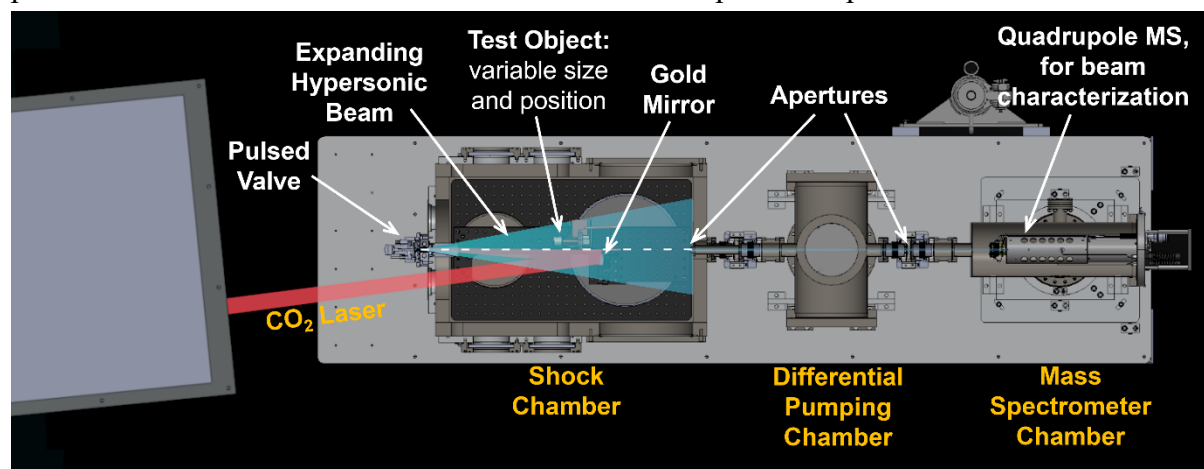


Figure 2. Diagram of the Table-Top-Shock Tunnel

throat, with the distance to the object and velocity distribution of the beam yielding a minimum pulse width (fwhm) of ~ 20 μ s. The mole fractions of the species in the hypersonic beam and their velocity distributions are characterized using the time-of-flight method by a differentially pumped mass spectrometer (base pressure $\sim 10^{-9}$ Torr). Based on earlier studies, we assume that O and O₂ produced from the source operating with pure oxygen as the precursor gas are in their ground electronic states, O(³P) [23] and O₂(³ $\Sigma_g^-) [24]. Unpublished results also suggest that N atoms produced with N₂ as the precursor gas are in their ground N(4S) state. Example$

characteristics of two beams that have been produced from either pure oxygen or nitrogen precursor gases are shown in Fig. 3. If desired in the future, the differentially pumped region (base pressure $\sim 10^{-8}$ Torr) could be used for additional characterization of the internal state distributions of the species in the beam, for example, by resonance enhanced multiphoton ionization (REMPI). CARS could be used in main chamber to measure the vibrational populations of molecular species, such as O₂ and N₂, in the beam (with the object removed). The entire length of the basic vacuum chamber portion of the instrument is ~ 2 m, and the lasers and detection equipment may be placed around this chamber. Thus, the entire facility is housed in the space of a typical university laboratory.

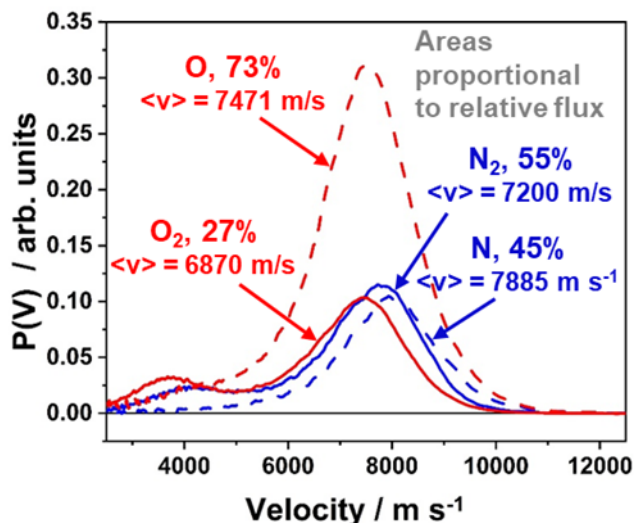


Figure 3. Velocity Distributions of Components of Two Hypersonic Molecular Beams. Red curves show the velocity distributions of the O and O₂ components of a beam formed from pure O₂ as the precursor gas. Blue curves show the velocity distributions of the N and N₂ components of a beam formed from pure N₂ as the precursor gas. Mole fractions of the atomic and molecular components of each beam are also shown

4. RESULTS AND DISCUSSION

Initial characterization of the TTST has been conducted by exposing Kapton H polyimide samples (125 μm thick) to a hypersonic O-atom beam, whose characteristics are shown by the red curves in Fig. 3. The choice to expose Kapton H for the initial study was based on the extensive knowledge of the effects of atomic oxygen on Kapton H, both in the low Earth orbital environment [25,26] and in hyperthermal O-atom beams in the laboratory [27]. In a highly rarefied flow of O atoms with $\sim 7.8 \text{ km s}^{-1}$ velocity, the erosion yield of Kapton H is known to be $3.0 \times 10^{-24} \text{ cm}^3 \text{ O-atom}^{-1}$. Therefore, by measuring the mass loss of Kapton H samples, with a known density of 1.42 g cm^3 , at a distance from the nozzle throat where the O atoms in the beam are largely unimpeded by gas-phase scattering above the surface (i.e., where gas compression above the sample is negligible), then the flux of the hypersonic beam may be determined. The beam flux at other distances from the nozzle throat may then be determined from the assumption of a $1/r^2$ dependence. Besides allowing for the determination of the beam flux, the use of Kapton

H provides insight into the formation of a shock above the sample surface through the examination of the surface morphology that develops as the surface is etched, as will be seen below.

Kapton H samples of 19 mm diameter were placed in a mount with an overall diameter of 25 mm. Samples were typically exposed to the beam at a variety of distances from the nozzle throat, from 20 cm to 65 cm, for 50,000 pulses of the hypersonic beam source, operating at a repetition rate of 2 Hz. The sample surfaces were oriented perpendicular to the streamlines of the flow at the sample center. In addition, the exposed samples were examined by scanning electron microscopy (SEM) and atomic force microscopy (AFM). In some cases, longer exposure durations were used. The masses of the samples were found by weighing them before and after exposure (with appropriate desiccation prior to each measurement).

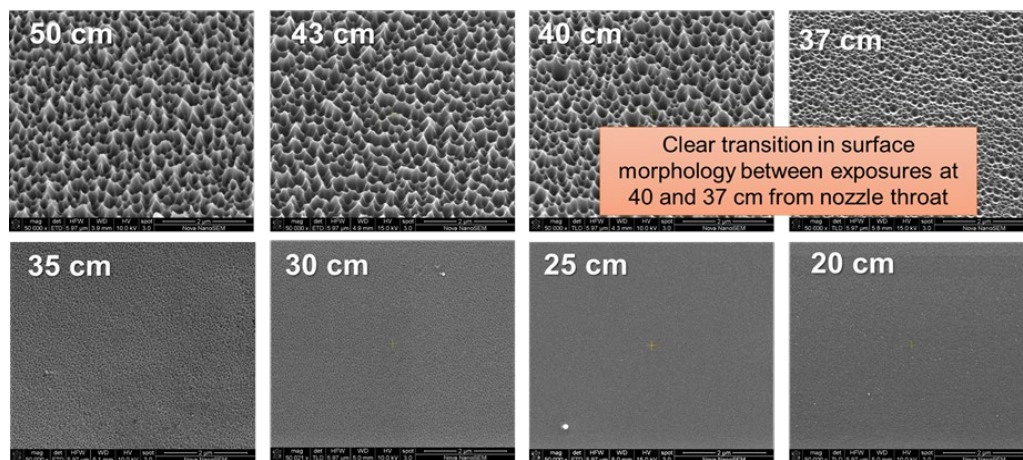


Figure 4. SEM Images of Kapton H Surfaces Exposed at Various Distances (as indicated) from the throat of the hypersonic nozzle. All SEM images were collected from the center of the exposed sample with a magnification of x20,000

As seen in Fig. 4, the surfaces that were etched at 40, 45, and 50 cm from the nozzle throat became very rough, similar (though not identical) to Kapton H surfaces than have been exposed to atomic oxygen in low Earth orbit [27], where the flow onto the surface may be assumed to be free molecular. There is an abrupt change in surface roughness, from rough to smooth, as the sample is brought closer to the nozzle, indicating that the development of the surface texture is very sensitive to the exact gas-surface conditions. The disappearance of surface texture is attributed to the increasingly broad angle of attack from impinging O atoms, which is expected when incident O atoms encounter a higher density of gas above the sample, resulting from the increasing O/ O₂ flux with decreasing nozzle-sample distance.

Near the transition region, where the surface roughness is changing rapidly with nozzle-sample distance, the surface roughness varies dramatically from the center of the sample to the outer edge. Fig. 5 shows a series of atomic force microscope (AFM) images from smaller to larger radii from the center of a single sample exposed at 37 cm from the nozzle throat. The transition to a smoother surface texture at this distance (Fig. 4) suggests that the etching of the Kapton H surface is no longer governed mainly by O atoms that strike the surface unimpeded. Thus, the

nozzle-throat-to-sample distance of 37 cm may correspond the formation of a weak shock above the surface. Quantitative examination of the surface roughness from the sample that was exposed at this distance shows that the surface roughness increased dramatically from the center to the edge. This observation is consistent with the supposition that a weak shock layer is causing gas-phase collisions to randomize the angles at which the incoming, high-velocity O atoms strike the surface and lead to a smoother surface texture. It is expected that the gas compression would be stronger at the center than the edges of the sample.

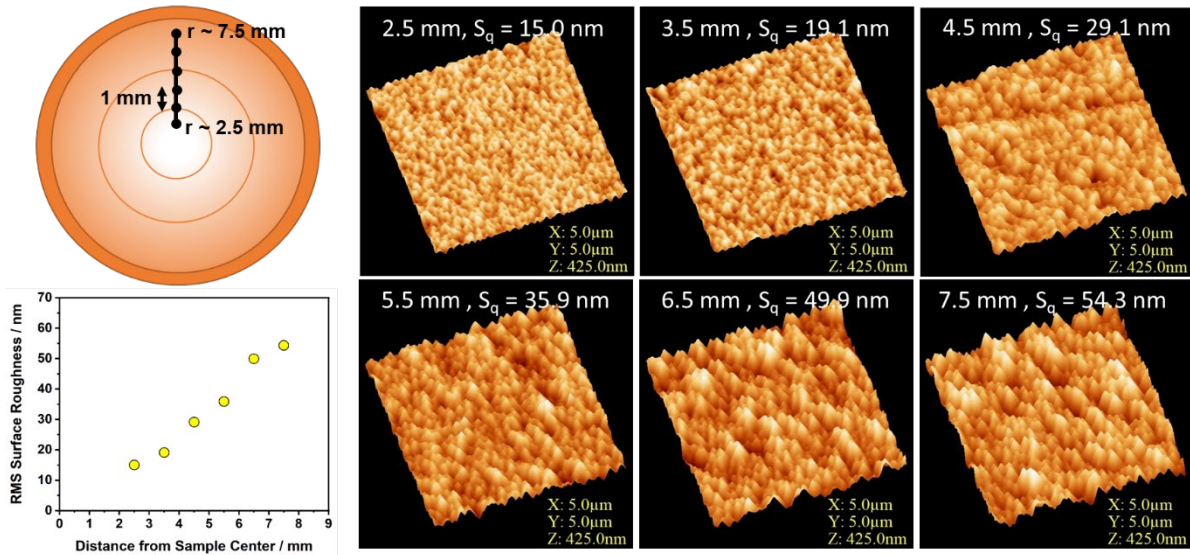


Figure 5. AFM Images of Kapton H Sample Exposed to the Hypersonic O/O₂ Beam at 37 cm from the nozzle throat as a function of distance from the center of the sample. The lower-left graph shows that the root mean square (rms) roughness changes by a factor of ~4 over the range of radii studied

Table 1. DSMC Simulation Conditions for this Study

#	Representative Distance / Condition	Freestream O Atom Flux (Molecules m ⁻² s ⁻¹)	Composition	ρ_{∞} (kg m ⁻³)	Velocity Sampling
1	20 cm	4.76×10^{25}	$\chi_{O} = 0.724$ $\chi_{O_2} = 0.256$	4.91×10^{-5}	V_X : Beam Distributions V_Y and V_Z : Boltzmann @ 10 K
2	25 cm	1.19×10^{25}		3.14×10^{-5}	
3	30 cm	4.64×10^{24}		2.18×10^{-5}	
4	35 cm	2.61×10^{24}		1.60×10^{-5}	
5	40 cm	2.00×10^{24}		1.23×10^{-5}	
6	45 cm	1.58×10^{24}		9.70×10^{-6}	
7	50 cm	1.01×10^{24}		7.86×10^{-6}	
8	65 cm	7.57×10^{23}		4.65×10^{-6}	
9	Low Earth Orbit	1.5×10^{19}	$\chi_{O} = 0.909$ $\chi_{N_2} = 0.091$	5.85×10^{-11}	(7500,0,0) m/s With 3D Boltzmann @ 1000 K

Direct simulation Monte Carlo (DSMC) calculations were performed by the Schwartzenruber group at the University of Minnesota to investigate the relationship between the gas-dynamic conditions above the samples and the observed roughness. They have used the Molecular Gas Dynamics Simulator implementation of the DSMC method developed at the University of Minnesota [28]. The simulation conditions are shown in Table 1 and the simulation domain is pictured in Fig. 6. They used the Variable Hard Sphere model for collisional cross sections, a constant collision number for rotational relaxation, and Millikan and White vibrational relaxation times.

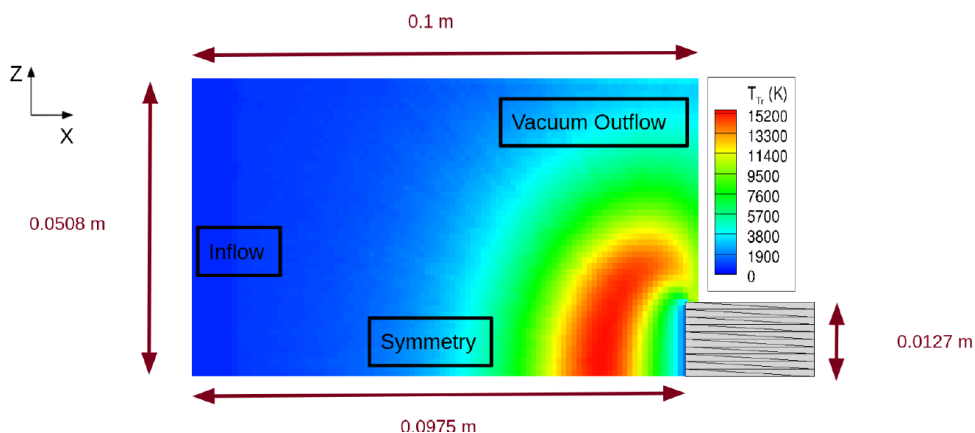


Figure 6. DSMC Simulation Domain

The inflow conditions were kept constant in time, and each simulation was run until it reached steady state, then results were sampled. Inflow flux was varied using the $1/r^2$ flux-distance relation in ratios corresponding to nozzle-sample distances of 20, 25, 30, 35, 40, 45, and 50 cm based on an estimate of the flux at 40 cm, obtained from the mass loss measurements of Kapton H at this distance. The estimated peak flux of O atoms at 40 cm from the nozzle throat was determined to be 2.0×10^{24} O atoms $m^{-2} s^{-1}$ during the $\sim 20 \mu s$ beam pulse. It was further determined that, during this short period, the compression above the sample quickly reached a steady state, so the DSMC calculations assumed a constant flux at the peak-flux value. The velocity distributions sampled for the x component of the velocity (V_x , perpendicular to the sample surface) were the measured O and O_2 distributions shown in Fig. 3. The V_y and V_z sampling distributions were assumed to be Maxwellian at 10 K. Rotational and vibrational

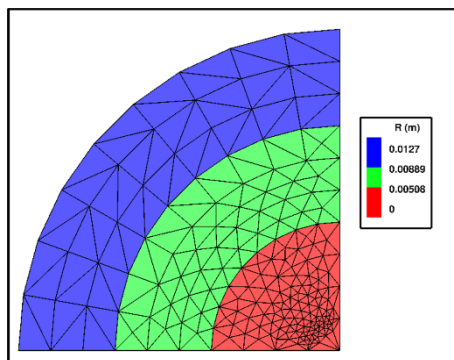


Figure 7. Target Face Split into Three Radial Regions, Labeled **Center, **Mid**, and **Edge** in Fig. 10.**

energies of O_2 were sampled from Boltzmann distributions at 2500 K. The mole fractions of the O and O_2 in the inflow were taken as the measured values (Fig. 3). The modelled diameter of the object corresponded to the actual diameter of the sample + holder (i.e., 25 mm). All atoms and molecules that struck the surface were assumed to desorb in thermal equilibrium at 22 °C, the sample temperature in the experiment. Characteristics of particles that impacted the surface were stored and plotted in distributions. The surface was split into three regions to characterize the changing surface flux at different radial stations, called Center, Mid, and Edge (see Fig. 7). An example of the simulated temperature profile of the flow over the test object at 25 cm from the nozzle throat is shown in Fig. 8.

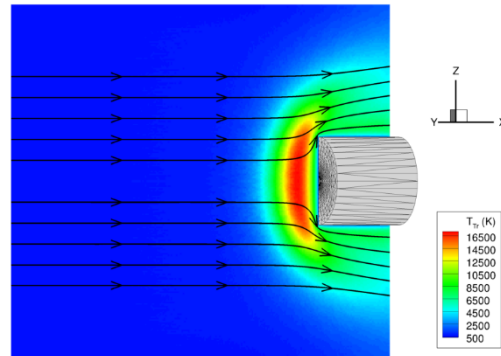


Figure 8. DSMC Simulation of the Temperature of the Flow over the 25 mm Diameter Object at 40 cm from the Nozzle Throat

Fig. 9 shows flux maps of O atoms that strike the centres of sample surfaces that were exposed at 20, 35, and 50 cm from the nozzle throat, as a function of velocity and impingement angle. Clearly, as the inflow density is lowered (i.e., increasing distance), the distributions have more of their flux at low angles and high velocities, implying that, as the distance is increased, the shock formed in the beamline becomes increasingly diffuse, and incoming O atoms are less likely to undergo gas-phase collisions before they impact the surface. The significant fraction of unimpeded O atoms is strongly correlated with the development of surface roughness, although the interplay between the effects of primary vs. secondary O-atom collisions on the surface texture is unknown at this time.

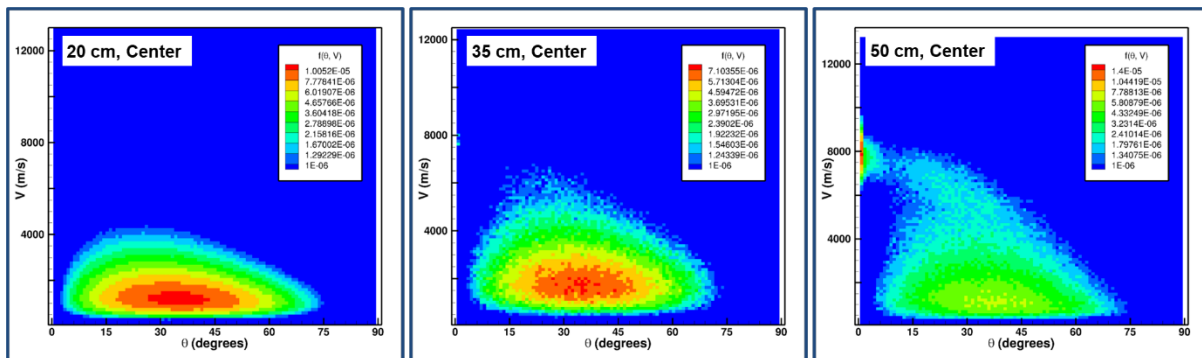


Figure 9. DSMC Results Showing the Relationship Between O-atom Velocity and Impingement Angle onto the Surface (with respect to the surface normal) for the Centers of Samples Exposed at 20, 35, and 50 cm from the Nozzle Throat.

The nozzle-sample distance that showed the largest change in the flux of unimpeded O atoms ($V \sim 8000 \text{ m s}^{-1}$) across the surface was 35 cm (see Fig. 10), which is very close to the distance (37 cm) where the largest difference in surface roughness was seen across the sample (see Fig. 4). The large difference between unimpeded particles across the surface is expected when the compression is such that the pressure at the stagnation point is sufficient to deflect most incoming atoms and molecules while the pressure near the outer edge of the sample is low enough to allow many O atoms to strike the surface unimpeded. The correlation between the calculated change in unimpeded O atoms and the rapid change in surface roughness is remarkable and suggests that the DSMC results capture the essential flow dynamics. These results predict that, under these initial experimental conditions, the density at the stagnation region for the sample at 20 cm from the nozzle is approximately $4 \times 10^{-3} \text{ kg m}^{-3}$, corresponding to a pressure of $\sim 4 \text{ Torr}$. Higher compression may be possible if the object is moved closer to the nozzle or if the nozzle throat diameter is increased allowing more gas to be processed by the laser, which has adequate pulse energy to produce beams with similar velocity and O/O₂ mole fractions having at least 1.5x higher flux. Higher fluxes may also be achieved by producing beams with lower velocities, for example, $6000 - 7000 \text{ m s}^{-1}$. With lower velocity and thus lower translational energy per particle, more gas can be processed with a given laser pulse energy.

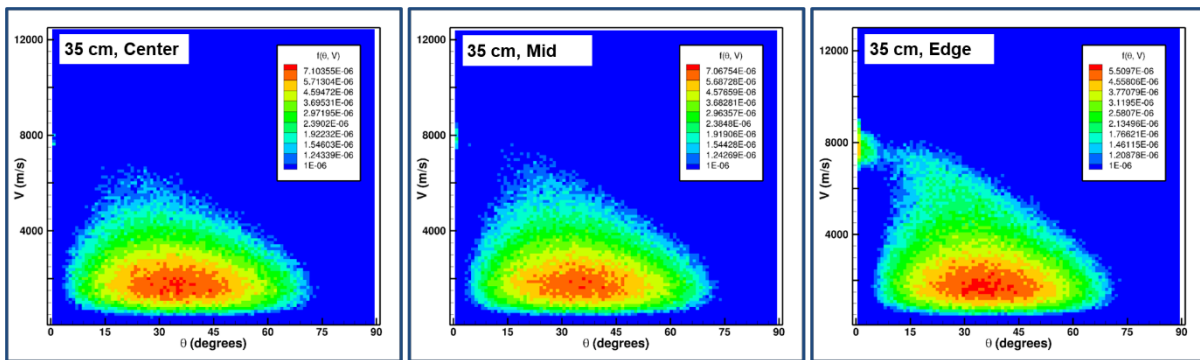


Figure 10. DSMC Results Showing the Relationship Between Particle Velocity and Impingement Angle onto the Surface (with respect to the surface normal) for a Sample at 35 cm from the Nozzle Throat, at the Sample Center, Mid, and Edge

5. CONCLUSIONS

Current hypersonic ablation models are empirical and are unable to predict conditions in a hypersonic shock layer, and new models under development are limited by the paucity of high-quality data needed for their refinement and validation. A new approach, referred to as a table-top shock tunnel (TTST) has been developed for measuring shock layer chemistry and conducting rapid and low-cost materials testing under relevant hypersonic conditions. The approach is to use existing laser-detonation technology, optimized for high flux operation, to produce a hypersonic pulsed molecular beam, which, when targeted at a small blunt object, can generate a hypersonic shock layer that exhibits highly relevant shock layer chemistry. Initial experimental studies of Kapton H ablation by a hypersonic O/O₂ beam in conjunction with DSMC calculations confirm the presence of a shock layer above a 25 mm dia. test object. This shock layer, while rarefied, is a repeatable nonequilibrium environment that may be exploited for hypersonics research and testing. While the initial tests are promising, further enhancements are envisioned that would produce higher densities in the shock layer. In addition, beams with various mole fractions of O, O₂, N, N₂, and NO are envisioned. Thus, the TTST represents an approach to materials testing and studies of nonequilibrium chemistry in a hypersonic flow environment that can be produced in a laboratory-scale instrument. Unlike large shock-tunnel facilities, the beam, and therefore the shock layer, can be generated (pulsed) 2-3 times per second for hours or even days with repeatable conditions. Such test frequency and repeatability will enable existing optical and mass spectrometric diagnostic techniques to measure thermochemical quantities in realistic nonequilibrium chemistry conditions with unprecedented accuracy and precision at a small fraction of the cost compared to existing shock tunnel facilities. The new capability can also provide rapid screening for emerging materials and allow informed selection of materials for more expensive tests in high-enthalpy test facilities. Results obtained so far indicate that the TTST is a promising new and complementary tool in the hypersonics community that can produce data for nonequilibrium dissociation, vibrational and rotational populations, gas-surface interactions, and material response phenomena. The first publication on the design and initial performance of the TTST is currently in preparation.

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APPENDIX A: DETAILS OF CONSTRUCTION, PERSONNEL SUPPORTED, AND TIMELINE

The funds provided by a DURIP award (FA9550-19-1-0112) have covered the cost of designing the TTST system and the purchase of almost all relevant custom vacuum chambers and other custom hardware, vacuum pumps, valves, gauges, a hypersonic molecular beam source, a new high-pulse-energy CO₂ TEA laser, and a mass spectrometer to characterize the hypersonic beam. Subsequent funding to construct the apparatus came from other sources, a key source being the AFRL grant. A photograph of the operational system is shown in Fig. A-1.

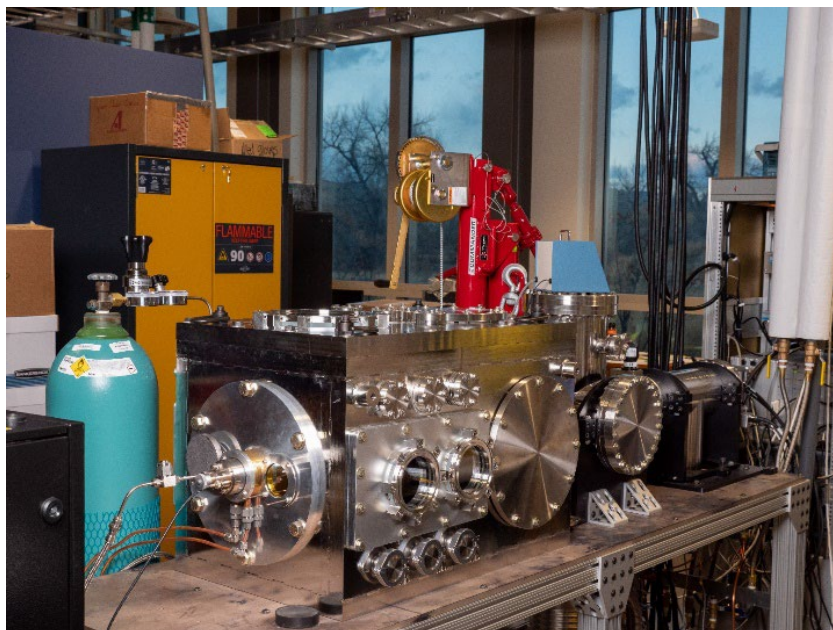


Figure A-1. Photograph of the Operational TTST System

The timeline for the design and construction of the TTST system was significantly longer than the typical one-year period for a DURIP award, largely because the PI changed universities before all the custom and commercial hardware was delivered. The project began in March of 2019, when the PI was on the faculty of Montana State University, Bozeman. A local machining and engineering design company, Autopilot, was contracted to generate the drawings of the TTST system and the bill of materials, as well as to fabricate several custom parts. This work was done under the direction of the PI, with significant assistance from two post-docs, Dr. Sara Marquez and Dr. Chenbiao Xu. Dr. Marquez was the key person from the PI's group who oversaw the progress of the custom equipment fabrication and the procurement of all the commercial hardware. She conducted research on the needed equipment, obtained bids as required for the high-value items, provided specifications to vendors, organized the equipment as it arrived, and followed progress with the use of spreadsheets. She worked with the PI's lab manager, Ms. Nicole Wolf, who took care of payment for all the custom and commercial equipment that was ordered. The design phase of the project was completed by the end of August 2019, and then all the equipment was ordered during the fall of that year. Many of the vendors

did not meet their stated delivery dates, and before the one-year anniversary of the project in March of 2020, a no-cost extension of the DURIP award for one year was requested and was granted. Shortly after that time, in April of 2020, the PI received an offer for a faculty position at the University of Colorado Boulder, which he accepted. His new position started in August of 2020, and he moved all his laboratory equipment from Montana State University to CU Boulder in three shipments, two in September 2020 and one in November 2020. A significant fraction of the TTST equipment had not been delivered by the time the PI knew he was going to move, so the equipment was stored as it arrived, and most items were not unpacked from their shipping containers. All the TTST-related equipment had arrived at Montana State University by August of 2020, and it was moved with the other equipment from the PI's lab to CU Boulder in the shipments that followed in September and November. The only member of the PI's group to move to CU Boulder was Dr. Xu, and he assembled the basic vacuum system of the TTST during the fall of 2020. Dr. Xu has not been supported by the AFRL grant, and his work for the TTST project has been supported by the PI's startup award at the University of Colorado Boulder. The whole system could not be completed in the fall of 2020, because construction work still needed to be done to install the utilities (electricity, power distribution, cooling water, vacuum pump exhaust) to make the PI's new lab functional. The construction work was delayed and was not completed until early July 2021. A new graduate student (Mr. Brian Riggs) had joined the group several months earlier and had been assigned to the TTST project. He and Dr. Xu completed the assembly of the TTST and tested the vacuum system during July and August of 2021. Mr. Riggs was, throughout the project, largely supported by the AFRL grant which is the subject of the current report. During the set-up of the system, Dr. Xu and Mr. Riggs encountered many obstacles. Several additional pieces of custom and commercial hardware were required, and these were acquired with funds provided by the PI's startup funds from CU Boulder. The most significant obstacle was the new CO₂ laser, which was needed for the hypersonic beam source. The only suitable manufacturer of this type of laser is located in South Africa. It turned out that the laser was damaged during shipment from South Africa to Montana State University, but the extent of the damage was not discovered until the laser was set up at CU Boulder about one year later. Ordinarily, the laser company (PaR Lasers) would send a technician to set up the laser, but the technician was initially not able to travel because of COVID travel restrictions. Therefore, a company representative tried to talk Mr. Riggs and Dr. Xu through the repairs of the laser. After two months, the laser was still not functional, and a technician was eventually able to travel to Colorado, where he resolved most of the problems. Some small remaining problems were resolved by Mr. Riggs and Dr. Xu in the fall of 2021 with the guidance of personnel from PaR Lasers. Finally, in late October of 2021, the first demonstration of the hypersonic beam in the TTST was realized. Around this time, another person started helping with the project: a sabbatical visitor, Dr. Irina Gouzman, from Soreq NRC in Israel. Dr. Gouzman is an expert in the surface characterization of materials by profilometry, scanning electron microscopy (SEM), atomic force microscopy (AFM), and X-ray photoelectron spectroscopy (XPS), and her main contribution has been in the analysis of sample materials that have been exposed to a hypersonic O-atom beam in the TTST. From October 2021 until the writing of this report (September 2022), many test experiments with the hypersonic beam of the TTST have been conducted, with and without samples in the chamber.

Thus, the TTST has been brought to fruition and given substantial value by the contributions of various people and funding sources. As mentioned above, the construction of the TTST and its

initial testing were accomplished with the assistance of two post-docs, a graduate student, a research staff member, and a sabbatical visitor. The labor for the first year of the project was funded by an AFOSR grant (FA9550-17-0057) that was ongoing at Montana State University when the DURIP award was received. The move of the equipment to CU Boulder, the initial setup of the TTST, and several items needed ultimately to make the system functional were funded by the PI's startup funds at CU Boulder. The sabbatical visitor was also supported by these funds. Since September 2020, most of the support for the graduate student at CU Boulder (Mr. Brian Riggs) has come from the AFRL grant (FA9453-20-1-0052). Further support for Mr. Riggs has come from Sandia National Laboratories (AWD-20-10-0064). The Sandia project is in support of their Laboratory Directed Research and Development program entitled "Predictive, Agile Reentry Tools (PART): Pyrolysis and Transpiration." The interest of the AFRL is in supporting HYPREP (Hypersonic Plasma Reentry Effects Program). This program is concomitantly funding Prof. Thomas Schwartzenuber (University of Minnesota) to conduct modeling simulations of the hypersonic beam and the characteristics of the shock layer that is formed above a sample surface. These simulations have been critical in the interpretation of the experimental data and in the characterization of the new TTST facility, and they are expected to guide future experiments with the goal of providing data that are valuable for the development and validation of new aerothermodynamic models of hypersonic flow around objects.

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