



Measurements, Modeling and Control in Nonequilibrium in Shock-Boundary Layer Interaction

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<p>14. ABSTRACT</p> <p>Shock-boundary layer interactions can induce flow distortion and impair vehicle performance, create flow separation with loss of control authority, and result in severe localized heating rates. In hypersonic flight, the problem is extremely challenging due to the nonlinearity of the thermal-chemical-fluid mechanics coupling and the broad range of length and time scales exhibited. Correct prediction of the peak heat transfer rates is critical to vehicle survival, however a recent NATO workshop revealed severe underprediction of the transient thermal loads by state-of-the-art simulations in high enthalpy, air flows of interest to the Air Force (Knight et al 2012). Shock interactions which respond on the measurable macroscale to changes in the molecular processes also provide valuable diagnostic tools for development and validation of thermochemical models recently developed in response to Air Force needs.</p> <p>Shock wave-boundary layer interaction experiments over double wedge and double cone geometries in hypervelocity flows are reported. Experiments are conducted in two complementary high-stagnation enthalpy impulse facilities which provide the flexibility to access a range of test conditions with undissociated freestream (Hypervelocity Expansion Tube, HET), achieve long test times (T5 Free Piston Shock Tunnel), and examine facility independence of the results. Diagnostics include surface heat transfer measurements, high-speed schlieren and chemiluminescence imaging, and spectroscopic species and temperature measurements. These experimental capabilities permit direct measurements that dissect the anatomy of the shock-boundary layer structure and use this model problem as a diagnostic tool to help resolve the interplay between the fluid mechanics and coupled chemical and thermal processes in the gas.</p>		
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Final Report for Award "Shock-Boundary Layer and Shock-Shock Interactions in Nonequilibrium"

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Joanna M. Austin, Nelson J. Yanes, Andrew Knisely

March 29, 2019

Report Summary

Shock-boundary layer interactions can induce flow distortion and impair vehicle performance, create flow separation with loss of control authority, and result in severe localized heating rates. In hypersonic flight, the problem is extremely challenging due to the nonlinearity of the thermal-chemical-fluid mechanics coupling and the broad range of length and time scales exhibited. Correct prediction of the peak heat transfer rates is critical to vehicle survival, however a recent NATO workshop revealed severe underprediction of the transient thermal loads by state-of-the-art simulations in high enthalpy, air flows of interest to the Air Force [1]. Shock interactions which respond on the measurable macroscale to changes in the molecular processes also provide valuable diagnostic tools for development and validation of thermochemical models recently developed in response to Air Force needs.

Shock wave-boundary layer interaction experiments over double wedge and double cone geometries in hypervelocity flows are reported. Experiments are conducted in two complementary high-stagnation enthalpy impulse facilities which provide the flexibility to access a range of test conditions with undissociated freestream (Hypervelocity Expansion Tube, HET), achieve long test times (T5 Free Piston Shock Tunnel), and examine facility independence of the results. Diagnostics include surface heat transfer measurements, high-speed schlieren and chemiluminescence imaging, and spectroscopic species and temperature measurements. These experimental capabilities permit direct measurements that dissect the anatomy of the shock-boundary layer structure and use this model problem as a diagnostic tool to help resolve the interplay between the fluid mechanics and coupled chemical and thermal processes in the gas.

High-speed shadowgraph and surface heat flux measurements have been obtained for three model geometries in two different facilities over a range of freestream conditions and gas compositions. The test conditions for the T5 experiments were selected to complement the capabilities of the HET. Double-wedge experiments in T5 were run utilizing the same model used in previous HET studies. Two new double-cone models were designed and instrumented with fast-response thermocouples to study boundary-layer separation over an axisymmetric body and the effects due to a varying flap angle.

Spectra and excitation temperature data were obtained in the post-bow shock region of the double wedge (freestream $h_o=8\text{MJ/kg}$, Mach = 7). NO A-state emission in the 212-250nm range was imaged using a streamwise-oriented slit for high spatial resolution. Radiation was collected along a line of length 6 mm at a location 6.1 mm above the triple point. The relaxation profile downstream of a bow shock in front of a 1" diameter cylinder was also interrogated. Cylinder results are compared against a zero-dimensional state-to-state model and a two-temperature, reacting Navier-Stokes simulation. Test gas O_2 mole fraction was varied from 30% to 120% of the air value to examine changes in relaxation profile.

The principal conclusions in this report are:

- (i) **Surface heat flux measurements of the laminar boundary layer for the double-wedge show good agreement between both facilities with proper nondimensionalization.** Heat flux measurements on the two double cone geometries were made in T5 and on the double wedge geometry in T5 and HET. The measured heat flux for the double-cone laminar boundary layer was found to be in agreement with analytical predictions and viscous single-cone simulations. Peak heating was measured for the double-cone for both models. With the 25-48 degree double-cone heating on the aft body was well predicted by the laminar correlations for air and nitrogen test gas. Peak heating was found to be slightly higher for the nitrogen than air. However, when the heat flux levels are normalized by the post-reattachment conditions the air and nitrogen are in good correlation to each other. Augmented peak heating was measured on the aft body of the 25-55 double-cone due to the post-reattachment impinging shock of the type V interaction. Higher heat

flux was measured with the nitrogen test gas. However, transient heat flux traces show that the heating is highly localized to the region around the impinging shock. Very high heating is measured when the impinging shock passes over the thermocouples. In the air condition, the impinging shock is located directly between two of the thermocouples. In the nitrogen condition the shock is located just upstream of the thermocouple leading to the high heat flux measurements. These results show that there must be a sufficiently high density of thermocouples in order to resolve the highly localized heat flux in the impinging interactions. Additionally, the impingement location is seen to be directly related to the location of the triple point which is partially determined by the bow shock standoff for the high-deflection angle double-cone model. One observable effect of the nonequilibrium is an increase in the post bow shock density ratio which has been seen to increase the stand off distance which affects the shock impingement location.

- (ii) **High-speed shadowgraph movies of flow establishment and assessment of flow unsteadiness.** A finite startup time is observed in T5 and the HET through high-speed shadowgraph and heat flux data. The startup process for each facility is different and must be accounted for in order to be accurately replicated by simulations. In T5 the nozzle reservoir pressure experiences a finite rise time to a steady stagnation value. This rise time must be taken into consideration when defining a flow startup time. No transient shock structures are observed with the double-cone model in T5 after the stagnation pressure within the nozzle reaches a constant level. Any large scale fluctuation in the heat flux was found to be directly correlated to flow structures seen in the high-speed images. Steady flow is also observed with the double-wedge for an air test gas in T5. Good correlation of the scaled heat flux for the laminar region of the double-wedge was found to exist between the HET and T5 experiments. However, the boundary-layer separation with a nitrogen test gas was seen to be unsteady. It is currently unclear why this is the case as previous studies with the same geometry, flow conditions, and aspect ratio have observed steady flow.
- (iii) **New high speed videos provide evidence that startup processes in an expansion tube play an important role in the development of flow separation before the arrival of the test gas.** In the HET, two conditions with a test gas Mach number of 7 and stagnation enthalpy of 8 MJ/kg were run with different acceleration gas composition and conditions. The flow is initially started with post shock acceleration gas, resulting in initial separation of the boundary layer. For helium as an acceleration gas, the duration of the post shock helium is 60 μs , allowing the separation region to grow and have initial length before the arrival of the test gas. For an air acceleration gas, the duration of the post shock acceleration gas is on the order of 10 μs . In this situation, it is observed that the test gas arrives with minimal separation at $t = 0 \mu\text{s}$. This is more faithful to time resolved state-of-the-art simulations, where the test gas is typically impulsively started over the double wedge and separation begins at the hinge.
- (iv) **Applying windowed proper orthogonal decomposition on videos provides insight on the important flow structures in a shock wave-boundary layer interaction.** Time dependent data can be decomposed into spatial modes and temporal parts through an orthogonality relation. Physically important features can be extracted, as well as their corresponding temporal content within the duration of test time. Analysis reveals that the magnitude of the second and higher modes is greatest at the bow shock location, separation bubble, reattachment shock, and a significant portion of the lead oblique shock. This indicates that most of the temporal variations occur at these regions.
- (v) **A new diagnostic for spatially resolved emission spectroscopy was applied to a shock wave-boundary layer interaction.** By projecting the image of the slits at the centerline of the test article, radiation can be collected along a line. This results in a detector image where one axis is streamwise position and the other axis is wavelength content. The intensity of the image provides insight in the population of the A-state NO molecules. By binning portions of the detector along the streamwise axis, spectra can be extracted and fitted. The final result is an excitation temperature profile as a function streamwise position. Post shock relaxation was successfully measured behind the bow shock of double wedge flow. A measured rise in temperature was also observed near the location of the shear layer.
- (vi) **Using stagnation flow as a case study, vibrational and rotational temperatures were extracted from experimental spectra with varying O_2/N_2 freestream mole fractions.** Spatially resolved emission spectra were collected in hypervelocity flow over a 1 in diameter cylinder. Changing the wavelength range to 210-250 nm allows for the (1,0) peak in the emission to be visualized. The ratio of the (1,0) and the (0,0) peak is a strong function of vibrational temperature, allowing for the extraction of two temperatures. Reducing the oxygen content in the freestream reduces the quenching of excited states, allowing for additional A-state NO to become present. The

result is increased radiance along the stagnation streamline and a rise in excitation temperatures.

The award has supported the work of two graduate students, with one student completing his PhD in 2016 and the other continuing towards expected graduation in 2020. Results of this research were disseminated in 6 archival publications, 6 invited talks, and 2 conference presentations. Additional journal articles are in preparation and data will be disclosed when these articles are published.

Publications

1. Yanes, N.J., and Austin, J.M., Nitric Oxide spectroscopic measurements in a hypervelocity stagnation flow, AIAA Scitech Forum, Paper 2019-0794, 2019.
2. Knight, D., Chazot, O., Austin, J.M. et al. Assessment of predictive capabilities for aerodynamic heating in hypersonic flow, Prog. Aerospace Sciences 90:39-53, 2017.
3. Knisely, A.M. and Austin, J.M., Geometry and test-time effects on hypervelocity shock-boundary layer interaction, 54th AIAA Aerospace Sciences Meeting, San Diego CA, 2016.
4. Knisely, A.M., Experimental Investigation of Non-equilibrium and Separation Length Scaling in Double-Wedge and Double-Cone Geometries, PhD thesis, University of Illinois at Urbana-Champaign, 2016.
5. Tumuklu, O., Levin, D.A., Gimelshein, S.F. and Austin, J.M., "Modeling of near-continuum laminar boundary layer shocks using DSMC, 30th Int. Symp. Rarefied Gas Dynamics, Victoria Canada, July 2016.
6. Tumuklu, O., Levin, D.A., Gimelshein, S.F. and Austin, J.M., "Factors influencing steadiness in laminar boundary layer shock interactions, 30th Int. Symp. Rarefied Gas Dynamics, Victoria Canada, July 2016.