Measurements and Modeling in Nonequilibrium Shock/Boundary Layer Interaction

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Hallmark of hypervelocity flight: Nonlinear coupling of fluid & thermochemistry

Hypervelocity freestream

\( h_t \sim 9 \text{ MJ/kg} \)
\( U \sim \text{km/s} \)
\( T \sim 800\text{K} \)

Gas phase reactions

Laminar inflow boundary layer

Gas surface reactions

Shock-dominated turbulent flow

Difference in peak heating
Shock distortion of hypervelocity boundary layer

- Shock-boundary layer interactions:
  - Unsteady, potentially extreme, aerodynamic loads
  - Flow separation with loss of control authority
  - Severe heating rates
- 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 the high enthalpy, air flows of interest to the Air Force.

Our approach is unique in several ways:
1) Experiments in two high-enthalpy facilities.
   - Range of test conditions with undissociated freestream (Hypervelocity Expansion Tube)
   - Up to 25 MJ/kg with 1ms test times (T5 Free Piston Shock Tunnel)
   - Examine facility independence
2) Diagnostics beyond mean flow measurements: Spectroscopy and High-Speed Imaging.
   - Direct measurement of naturally-occurring species and temperatures
   - Overlay with flow structure visualizations
   - Dissect the interplay between real gas effects and flow processes
3) Close collaboration with high-fidelity simulations for hypersonic, reacting flows.
Previous results: Quantifying response to changing chemistry

Edge tracking extracts shock surfaces from high speed images.

Freestream oxygen percentage compared to air.

“Transition” possible at 80%. Supported by temperature measurements.

Further investigation of correlation with heat transfer.
To resolve existing discrepancies in heat flux prediction for hypervelocity shock/boundary layer interaction, we need:

Experimental data that are more than mean flow, surface measurements.
- Direct NO emission measurements (known sensitivity to thermochemistry).
- Time-resolved imaging and surface fluctuations.
- Assessment of facility effects

Simulations that are more than 2D, steady-state calculations.
- Reaction must be included at enthalpies greater than ~ 5 MJ/kg.
- Direct comparison of time-slices during flow evolution.
- Assessment of 3D effects (even for conical flow).
State-of-the-art CFD simulations and experiments show:

• Poor agreement in high enthalpy air flows ($\geq 5$ MJ/kg)
• Good agreement at lower enthalpies and N$_2$ flows (Olejniczak et al. (1999); Wright et al. (2000); Nompelis et al (2003, 2005, 2010))

Outstanding questions remain: freestream conditions, flow steadiness, and thermochemistry

Experiments in two, complementary, high enthalpy facilities

• Range of test conditions with undissociated freestream (Hypervelocity Expansion Tube)
• Up to 25 MJ/kg with 1ms test times (T5 Free Piston Shock Tunnel)
• Examine facility independence

Quantify viscous and inviscid flow features:
Direct spectroscopic measurements, High-speed Imaging
High enthalpy facilities: Hypervelocity Expansion Tube (HET)

- 152 mm ID, 9.14m length impulse facility
- Mach Numbers from 3-7.5
- Stagnation enthalpies from 2-9 MJ/kg
- Test times from 100 μs to 500 μs

(Dufrene, Sharma, Austin, JPP 2007)

Diagnostic capabilities
- Pressure Measurements
- Schlieren (single frame & high speed)
- Heat transfer measurements
  - Coaxial thermocouple
  - Platinum thin film gauges
- Emission spectroscopy
- Pressure Sensitive Paint
High enthalpy facilities:
T5 Free Piston Reflected Shock Tunnel

- Mach 6
- Stagnation enthalpies up to 25 MJ/kg
- Test times ~ 1ms
Test conditions and models

Test conditions: N<sub>2</sub>, air, varying O<sub>2</sub> content

<table>
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<th>Test Condition</th>
<th>M</th>
<th>ht</th>
<th>T, K</th>
<th>P, kPa</th>
<th>ρ&lt;sub&gt;t&lt;/sub&gt;, kg/m&lt;sup&gt;3&lt;/sup&gt;</th>
<th>u, km/s</th>
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<td>0.0071</td>
<td>1.97</td>
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</table>

25º-55º cone
- RTO studies

30º-55º wedge
- Scale model of Davis & Sturtevant

30-55 Double Wedge L=2”, b=4”

25-55 Double Cone d<sub>1</sub>=0.984”, d<sub>2</sub>=2.5”
Differences between Air and N2
Comparisons with DSMC simulations

Ozgur Tumuklu and Deborah Levin

2D N₂

3D N₂

Reacting air

Ozgur Tumuklu and Deborah Levin
Spanwise effects: preliminary results

- Designed using $\delta_1/W \sim 10$ from Ball (AIAA J 1971)
- Top down imaging
- Off-center gauges
- Varying model span
Flow timescales: Discrepancies

Experiments
Holden (AIAA J 1971)
- Skin friction, pressure, and heat transfer for separated base and compression ramp flows in a reflected shock tunnel facility with flow enthalpies of 3–20 MJ/kg.
  - Based on quantities reaching 98% of the final steady mean level.
- Times comparable to the estimated propagation time for an acoustic disturbance from the corner.

Substantially greater establishment times have been reported in several numerical studies.
- Gaitonde et al. - minimum of 100 flowtimes required to reach steady solution in N₂
  - based on surface integrated rms pressure & heat transfer over the whole surface reaching a constant value.
- Druguet et al. reported similar results.
  - Simulations of N₂ flow required 150 flow times to steady state based on the separation zone size, as well as numerical residual decrease by five orders of magnitude.
- NATO AVT136 - For low enthalpy/low density case, experiment reported steady, while 6 simulations reported significant time dependence.
Flow evolution in time

- Viscous processes: surface measurements

- Inviscid processes: Shock front tracking using high speed schlieren

Swantek and Austin, AIAA J, 2014
High speed schlieren: $N_2$ and Air

Double Wedge
M7_8

Top: Air
Bottom: $N_2$

100,000 fps
7 fps playback
1ms exposure
200 µs test time
Triple point establishment process: moving upstream
Comparison of viscous and inviscid times

**M7_2**

$t_{\text{test}} = 7.0$

**M7_8**

$t_{\text{test}} = 11.0$

Boundary layer prediction from Gupta (1972): $t = 3.3 \cdot L/U_\infty$
Testing in two facilities: T5 and HET
Simulations of flow evolution with chemistry

Ozgur Tumuklu and Deborah Levin

N\textsubscript{2}

Reacting air
Comparison of Air, Nitrogen, and Argon

- Smallest shock movement observed in the reacting air flow.
- The translational temperature values decrease at the starting point of the shear layer due to substantial energy dissipation by viscous flow.
- Argon results show that the effects of three-dimensionality on the flowfield parameters may be even stronger compared to nitrogen case.
Comparisons of HET spectral NO data with line-by-line spectral simulations

Assuming a single internal temperature

Significantly improved fit to data with both rotational and vibrational temperatures included

Simulations by Deborah Levin
Conclusions

- Mean heat transfer and shock configuration data available NATO STO 205.
- Quantifying dependence of heat transfer, shock configurations, chemiluminescence, and temperature for high enthalpy N$_2$ through to Air. Indication of transition at 80% O$_2$.

*Flow evolution experiments*
- Timescales for viscous and inviscid processes are same order of magnitude.
- Normalized establishment times of 2–8 are measured, in reasonable agreement with existing experimental data from surface gauges (6–11).

*3D, reacting simulations*
- DSMC 2-D and 3-D simulations for N$_2$ flows and experimental heat rates values are in a good agreement with 3-D case, especially in the aft part of wedge.
- For air, 2-D results in qualitative agreement with experiments, but, there may still be smaller 3-D effects which will be verified with 3-D simulations.

*Spectroscopic results (ongoing)*
Quantification of link between thermochemical activity and flow with schlieren and:
- Chemiluminescence (global, qualitative)
- NO emission temperature measurements: SWBLI & canonical geometries (point, quantitative)
Next steps

• Conical model testing
  – examining effect of geometry on post-reattachment shock
• Continue spanwise measurements
• Spectral measurements (species & temperature)
• Modeling and simulation for interpretation of flow structures and spectroscopy through the use of particle kinetic approaches
Technical challenges remaining

• Measurement of chemical species and vibrational temperature of at high temperature conditions to address inadequacies in NO and N$_2^+$ modeling.

• Using UV spectral emissions from these key radiators to provide clues about associated critical reaction pathways and thermal transitions for the gas and gas-surface reactions at experimental conditions, including the relevant molecular attributes that would suggest similar behavior in other species.

• Examine discrepancies between simulations and experiments of hypervelocity SWBLI investigating:
  – Regions of thermochemical activity as a function of freestream enthalpy and chemical composition
  – Facility dependence/independence of data for same geometries
  – Flowfield evolution and potential unsteadiness coupling with the chemical reactions.

• Possible control of flow separation and peak heating
Publications
(supported by previous award)

• Swantek, A.B. and Austin, J.M. Heat transfer on a double wedge geometry in hypervelocity air and nitrogen flows, 50th AIAA Aerospace Sciences Meeting, Nashville TN, Jan 2012.

Pending:
• Swantek, A.B., Knisely, A. and Austin, J.M., Heat transfer and separation length scaling in hypervelocity air and nitrogen flows over double wedge and cone geometries, to be submitted to AIAA Journal.
Business Update: Austin

• Award anticipated late August 2015, includes support for senior graduate student.

• Lab renovation supported by Caltech startup:
  – New lab completion due end of July.
  – Upgrade of T5 Data Acquisition System completed.
  – Upgrade of T5 laboratory space completed.

• Related programs with other Govt agencies:
  – FY 2014 AFOSR DURIP for spectroscopic measurements
  – NASA testing of MSL geometry