Testing a Full-Scale Hayabusa Model in a Large Expansion Tube

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Background

The Facility

Experimental Setup

Experimental Flow

Experimental Results

Conclusions
Radiating Shock Layer

Chemical kinetic process along stagnation line for Earth

[1]
Energy Ratio (Goulard Number)

- Nondimensional parameter to quantify level of coupling between radiation and convection [2]

\[ \Gamma = \frac{4\rho_{es}\chi_{es}\delta\sigma T^4}{\rho_\infty u_\infty h_{es}} = \frac{\text{Radiative Flux}}{\text{Total Energy}} = \frac{2q_R}{\frac{1}{2}\rho_\infty u_\infty^3} \]

- Larger values for \( \Gamma \) result in larger deviations in convective heat transfer with coupling
Some Values of $\Gamma$

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>$\Gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titan Explorer</td>
<td>0.167-0.453, 0.3</td>
</tr>
<tr>
<td>Galileo</td>
<td>0.1</td>
</tr>
<tr>
<td>Stardust (66km altitude)</td>
<td>0.022(^1)</td>
</tr>
<tr>
<td>Moon Return, Fire II</td>
<td>0.01</td>
</tr>
<tr>
<td>Hayabusa</td>
<td>0.008, 0.013</td>
</tr>
</tbody>
</table>

- In general, $\Gamma$ increases with increasing velocity and nose radius and decreasing altitude
- $\Gamma > 0.01$ indicates strong coupling

\(^1\) Calculated using correlation by Tauber and Sutton [3]
See [4],[5],[6],[7]
Radiative Coupling

- If $\Gamma > 0.01$, flowfield and radiation are said to be strongly coupled.

- Radiation heat loss from flow decreases enthalpy of gas.

- Shock layer moves closer to the body, although shock shape more or less remains the same [8].

- Density and velocity increase and temperature decreases.

- Radiative and convective heating rates at body can also be reduced [9].
Radiation Experiments

- Conserve $\rho L$ product and total enthalpy
  1. Reynolds number and viscous effects
  2. Binary chemical reactions
  3. Convective heat transfer
  4. Radiative transport if optically thin

- Fails to scale heat removed by radiation $(\rho L^3)$ and mass flux $(\rho L^2)$

- Not enough heat is removed from experimental flow field
Radiation Experiments

- Significant coupling results in flow field not being properly conserved with flight [10]
- Truncation of nonequilibrium region and low density issues [11]

- Is it possible to remove the effect of scaling by using a larger facility?
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Compression Tube

[Diagram of Compression Tube with dimensions and labels]

500mm
Length 14.122m

Secondary Driver
200mm
Length 9.772m

Shock Tube
180mm
Length 12.465m

Acceleration Tube
182.6mm
Length 17.644m

[Image of the Compression Tube facility]
Driven Tubes

- Reservoir
- Compression Tube: 500mm, Length 14.122m
- Secondary Driver: 200mm, Length 9.772m
- Shock Tube: 180mm, Length 12.465m
- Acceleration Tube: 182.6mm, Length 17.644m
- Nezelle
Mach 12 Nozzle

Image from Toniato’s PhD Thesis [12]
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A New Condition - Trajectory Point

Peak radiation according to Buttsworth, et al. [13], McIntyre, et al. [14] and Ohnishi, et al. [15]. Trajectory data from Ohnishi, et al. [15]
Experimental Flow Design

Fill Parameters

- Shock tube fill pressure: 2.5kPa
- Acceleration tube fill pressure: 3.5Pa

Analysis Tools

- Wall pressure sensors
- Instrument rakes at entrance and exit of nozzle
- PITOT, an expansion tube analysis tool which utilises equilibrium gas solutions [16]
Experimental Flow Design

Left: Test section rake (with conical caps installed)
Right: Rake at entrance of nozzle (designed by Toniato [12])
Experimental mode inputs

- Tube fill pressures
- Measured shock speeds
- Nozzle area ratio $A_{out}/A_{in}$
- Expansion factor

\[
\begin{align*}
9.5 \text{km s}^{-1} \times 1.1 & \equiv 10.0 \text{km s}^{-1} \times 1.045 = 10.45 \text{km s}^{-1}
\end{align*}
\]

- Shock velocity
- Expansion factor
- Shock velocity
- Expansion factor
- Expanded test gas velocity
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Shock Speeds

![Graph showing shock speeds with two lines representing Condition Quantification and Optical Measurements. The y-axis represents velocity in m s\(^{-1}\) ranging from 0 to 10,000, and the x-axis represents Tube Location in meters ranging from 0 to 45. The graph shows a steady velocity until a point labeled Tertiary Diaphragm, where the velocity decreases significantly. There is another point labeled Nozzle Inlet where the velocity drops further.]
Inlet Rake Pressures

- P1
- P3
- P4
- P5
- P7
- P8
- AT8 (right axis)

Pressure [kPa]

Time [s]
Pitot Pressures

![Graph showing Pitot Pressures over different time intervals and radii with error bars for shot 670 and shot 673.]
Now have the following experimental data

- Shock tube and acceleration tube wall pressure
- Conical pressure at nozzle entrance
- Conical and Pitot pressure at nozzle exit

Can estimate the test flow using PITOT experimental mode

- Vary nozzle area ratio and expansion factor
- Compare theoretical values to experimental measurements
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models
Shock Stand Off

![Graph showing comparison of different models and measured data against Suzuki, Kiharu, and Winter models.]

- 1:5 Model Spectra
- 1:5 Model HPV-1
- 1:1 Model Spectra
- 1:1 Model HPV-1
- X2 Measured
- X2 CFD Ideal
- X2 CFD Nozzle Inflow
- Suzuki
- Kiharu
- Winter

Time [ms] vs. δ/D
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Conclusions

- Designed an operating condition close to peak radiation
- High speed video measurements
- High speed spectroscopy measurements
- Compared shock stand off with literature values
  - 1:5 scale model measured larger shock stand off
  - Full scale model measured a lower shock stand off than values from literature


Questions?