The Effect of an Isogrid on Cryogenic Propellant Behavior and Thermal Stratification

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• Computational Modeling

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OVERVIEW
UPPER STAGE MODELING

Lockheed Martin
Atlas V 401

Boeing Delta IV Heavy


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MOTIVATION

- During LEO → GEO transfer, upper stage coasts for several hours
- Upper stage must re-start at conclusion of coast phase for insertion


Typical Delta 4 Medium launch sequence to geosynchronous transfer orbit from Cape

http://www.skyrocket.de/space/
WHAT CAN HAPPEN INSIDE TANKS?

- Stage exposed to solar heating
- Propellants (LH₂ and LOX) may thermally stratify
- Propellants may boil
- Slosh events during maneuvers

XSS-10 view of Delta II rocket: An Air Force Research Laboratory XSS-10 micro-satellite uses its onboard camera system to view the second stage of the Boeing Delta II rocket during mission operations Jan. 30. (Photo courtesy of Boeing.), http://www.globalsecurity.org/space/systems/xss.htm
WHY IS IT IMPORTANT?

- Propellant T&P must be within specified range for turbomachinery operation
  - If propellants outside specified T&P box engine may not restart
  - Orbit cannot be circularized

4-m Configuration (Delta IV-M, Delta IV-M+ (4,2))

- LH₂ Tank
- LOX Tank
- Modified Delta III second stage
- 4-m-dia LO₂ tank
- Delta III Pratt & Whitney RL10B-2 engine

5-m Configuration (Delta IV-M+ (5,2), Delta IV-M+ (5,4), Delta IV-H)

- 4-m-dia stretched LO₂ tank
- 5-m-dia LH₂ tank
- Delta III Pratt & Whitney RL10B-2 engine

ENGINE START AND OPERATIONAL REQUIREMENTS

• Propellants must be within a narrowly defined range of temperature and pressure to guarantee engine ignition (restart) at conclusion of coast phase
• Generic LOX map shown
WHAT HAPPENS WITH ISOGRID WALLS?

- Boundary layer profile important for mass flow (thickness of stratum) and heat transfer (temperature of stratum)
- In LH$_2$ tank isogrid wall is present
- Is this momentum and thermal boundary layer similar to laminar, turbulent or something different?
- What is influence of recirculation zones?
- Pursuing numerical and experimental work to assess boundary layer profile with full Gr and Re matching
COMPUTATIONAL MODELING
Computational Modeling: Introduction

- Forced flow CFD analysis over Isogrid performed
  - compared with flat plate analysis
  - boundary layer thickness compared to flat plate
- Results show Isogrid with 200-450% larger boundary layer compared to flat plate
- Good agreement in trends with windtunnel experiment
Computational Modeling: Introduction

- Forced flow CFD analysis give qualitative result to boundary layer thickness of Isogrid surface
- Free convective CFD models needed to properly asses stratification
- Framework first developed for smooth wall tanks; compared to theory

- Computational modeling done in FLUENT
- Free convective CFD model developed using
  - Unsteady coupled implicit solver
  - Boussinesq density model used ($\rho$ const. except in buoyancy term in mom. eq.)
Computational Modeling: Smooth wall

- Simulations run to check Ra scaling on smooth wall tanks
- Temperature contours compared after 10,000 seconds using non-dimensional temperature,

\[ \xi = \left( \frac{T - T_\infty}{T_{wall} - T_\infty} \right) \times 100\% = \left( \frac{\theta_{(x,y)}}{\theta_{wall}} \right) \times 100\% \]

- Map interpreted as:
  the results from [col. #] mapped onto the grid of [row #]
Computational Modeling: Smooth wall

- Ra scaling held extremely well at gravity levels below $10^{-1}$
- Ra scaling also checked between fluids (Water and LH2)
  - $< 7\%$ difference in results after 1 hour
Computational Modeling: Rough walls

- 2 roughness configurations
  1. 1/10 scale Isogrid baseline case
  2. Full-scale tank at 20% fill level

Velocity and temperature sampled at 9 vertical tank locations

<table>
<thead>
<tr>
<th>Location</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location 9</td>
<td>0.265 m</td>
</tr>
<tr>
<td>Location 8</td>
<td>0.235 m</td>
</tr>
<tr>
<td>Location 7</td>
<td>0.205 m</td>
</tr>
<tr>
<td>Location 6</td>
<td>0.175 m</td>
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<tr>
<td>Location 5</td>
<td>0.145 m</td>
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<td>Location 4</td>
<td>0.115 m</td>
</tr>
<tr>
<td>Location 3</td>
<td>0.085 m</td>
</tr>
<tr>
<td>Location 2</td>
<td>0.055 m</td>
</tr>
<tr>
<td>Location 1</td>
<td>0.025 m</td>
</tr>
</tbody>
</table>
EXAMPLE OF VELOCITY PROFILES AT LOCATION 1
JUST ABOVE 1st ISOGRID ELEMENT

CFD Velocity Profile Comparison @ Location 1 (y = 0.025)

- Isogrid, 50 s
- Isogrid, 100 s
- Isogrid, 150 s
- Isogrid, 200 s
- Smooth, 50 s
- Smooth, 100 s
- Smooth, 150 s
- Smooth, 200 s

Increasing time

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VELOCITY PROFILES AT LOCATIONS 1-9

CFD Velocity Profile Comparison @ Location 1 (y = 0.025)

Isogrid, 50 s
Isogrid, 100 s
Isogrid, 150 s
Isogrid, 200 s
Smooth, 50 s
Smooth, 100 s
Smooth, 150 s
Smooth, 200 s

CFD Velocity Profile Comparison @ Location 2 (y = 0.055)

CFD Velocity Profile Comparison @ Location 3 (y = 0.085)

CFD Velocity Profile Comparison @ Location 4 (y = 0.115)

CFD Velocity Profile Comparison @ Location 5 (y = 0.145)

CFD Velocity Profile Comparison @ Location 6 (y = 0.175)

CFD Velocity Profile Comparison @ Location 7 (y = 0.205)

CFD Velocity Profile Comparison @ Location 8 (y = 0.235)

CFD Velocity Profile Comparison @ Location 9 (y = 0.265)
TEMPERATURE PROFILES AT LOCATIONS 1-9

CFD Temp. Profile Comparison @ Location 1 (y = 0.025)

Increasing time
TEMPERATURE PROFILES AT LOCATIONS 1-9
Computational Modeling: Rough walls

- Various cases run featuring different heat loads and gravity levels
- Sample case shown (geometry 1), $g/g_0 = 10^{-2}$, $\theta = 5$ K, Water
- Rough wall tank compared to equivalent smooth wall case for constant wall temperature
  - Isogrid has larger thermal boundary layer,
  - larger boundary layer thickness,
  - $u_{\text{max}}$ dependant on Gr (inc. relative to smooth with inc. Gr)
Computational Modeling: Rough walls

- At low gravity levels, Isogrid mass flow rate larger; fluid entrained faster compared to smooth
- Energy flow rate also larger; stratum warms more
CONCLUSIONS

- Shown for low gravity levels that Isogrid boundary layers entrain fluid faster compared to smooth wall cases
- Results in an increase in stratification rate (up to 100% increase for certain geometries and spacecraft acceleration levels)
- Larger thermal boundary layers and increased heating area from Isogrid results in warmer stratum temperatures compared to smooth
- In addition, wall conduction is currently being added to models
SELECTED REFERENCES

Literature Review References:

Web-based References for Graphics:
• http://www.skyrocket.de/space/index_frame.htm
• http://www.skyrocket.de/space/doc_sdat/goes-n.htm
• http://www.boeing.com/defense-space/space/delta/delta4/d4h_demo/book01.html

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