An Improved Model of Cryogenic Propellant Stratification in a Rotating, Reduced Gravity Environment

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OVERVIEW: UPPER STAGE MODELING

Lockheed Martin
Atlas V 401

Boeing Delta IV Heavy


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OVERVIEW: WHAT CAN HAPPEN INSIDE TANKS?

- Stage exposed to solar heating
- Propellants (LH$_2$ and LOX) may thermally stratify
- Propellants may boil
- Slosh events during maneuvers
- Upper stage must re-start at conclusion of coast phase for insertion


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

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OVERVIEW: WHAT CAN HAPPEN INSIDE TANKS?

- 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
MOTIVATION

- Rotation present during missions to evenly heat spacecraft
- Effect rotation has on propellant thermal properties unknown
- Upgrade current analytical/numerical stratification models to include rotation

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MISSION PARAMETER RANGES

- **Tank Dimensions:**
  - Square 3 m diameter tanks

- **Cryogenics: LH\textsubscript{2}, LOX**
  - $T_{\text{bulk}}$ LH\textsubscript{2}: 16 K, 28.8 °R, -430.9 °F
  - $T_{\text{bulk}}$ LOX: 91 K, 163.8 °R, -295.9 °F

- **Tank Pressure (All Cryogenics):** 30 psi

- **Initial Fill Levels:** 10, 20, 30%

- **Heating Conditions:**
  - Constant wall temperature: $\theta = T_{\text{wall}} - T_{\text{bulk}}$: $\Delta T = 0.1, 0.5, 1.0$ K
  - Heat flux to fluid: 5-100 W/m\textsuperscript{2}

- **Reduced Gravity Environment:** $g/g_0 = 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}, 1$

- **Rotation rates:** $\omega = 0.1, 1, 5$ °/sec

- **Orbital Transfer Time (Simulation Time):** 2 – 4 HR

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MASTER MODEL: BASIC FRONT END OPTIONS

1. Tank geometry
   - Tank diameter, height
   - Square bottom

2. Boundary layer nature and heat transfer coefficient selection
   - Free convection
     • Laminar/Turbulent (w/ & w/out switching)

3. Wall temperature settings
   - Constant inner wall temperature
   - Constant inner wall heat flux

4. Rotation rate

5. Gravity level
GENERAL MODELING PHILOSOPHY

- Stratum growth $\Delta(t)$
  - $u(y)$ depends on if heating is constant wall temperature or constant heat flux, $q$
  - $u(y)$ depends on nature of boundary layer
  - Provides differential equation for $\Delta(t)$

- Stratum temperature, $T_s(t)$
  - Heat entering side wall into boundary layer is used to increase stratum temperature
  - Energy exchange with ullage negligible
  - $T_s$ assumed uniform

\[
\dot{m}_{bl} = 2\pi R \rho \int_0^{\delta} u(y) \, dy = \rho \pi R^2 \frac{d\Delta}{dt}
\]

\[
\dot{q} 2\pi RH = \rho \pi R^2 \Delta c_p \frac{dT}{dt}
\]
RELEVANT NON-DIMENSIONAL NUMBERS

- Grashof number, $Gr$, governs heat transfer regime for constant wall temperature
  - Ratio of buoyancy to viscous forces
  - $\beta$, Volumetric thermal expansion coefficient
  - $\theta$, Wall to Bulk temperature difference

$$Gr = \frac{g\beta\theta L^3}{\nu^2}$$

$Ra = Gr\ Pr$

- Rayleigh number, $Ra$, is product of Grashof and usual Prandtl number, $Pr$
- Prediction of boundary layer transition
  - If $Ra < 10^9 \rightarrow$ Laminar
  - If $Ra > 10^9 \rightarrow$ Turbulent

$$Gr^* = \frac{g\beta q_w L^4}{k \nu^2}$$

$Ra^* = Gr^* \ Pr$

- Modified Rayleigh number, $Ra^*$, for uniform heat flux

- Modified Grashoff number, $Gr^*$, governs heat transfer regime for uniform heat flux, $q_w$

- Others: Reynolds Number, $Re$ (momentum to viscous) Weber number, $We$ (inertial to capillary), Froude number, $Fr$ (inertial to body), and Bond number $Bo$ (body to capillary)
Ra and Ra* vs. g/g₀ MAPS for LH₂ and LOX

- Maps laminar or turbulent boundary layers possible for typical mission profiles (NIST data)

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WHAT IS IMPACT OF BBQ ROLL ROTATION:

Typical rotation rate, $\omega \sim 1^\circ/\text{sec}$

Shape at $g/g_0 = 1$, $\omega \sim 850^\circ/\text{sec}$

- Does $1^\circ/\text{sec}$ matter?
- Not at $g/g_0 = 1$ but in coast phase $g/g_0 \sim 10^{-4}$
  $\rightarrow$ significant dishing effect

Key Question: How does rotation impact results?
- Assume liquid is in solid body rotation (transients can also be treated)
- Model extra height that liquid gains along wall as a longer interfacial heat transfer length
- Center point in radial direction of tank is taken to be point where percent of bulk remaining is referenced $\rightarrow$ worst case scenario
- Trade off between heated area and surface area to distribute warm stratum
ROTATION / STRATIFICATION COMBINED MODEL

\[ h = \frac{(\omega R)^2}{2g} \]

Spin Rate, \( \omega = 1^\circ/\text{sec} \)

- \( g/g_0 < 10^{-3} \)
- \( g/g_0 = 10^{-4} \)
- \( g/g_0 = 10^{-5} \)

Note: Parabola bottoms out

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ROTATIONAL CASES

Re-examine boundary layer / stratum mass balance

\[ \dot{m}_{bl} = \pi R^2 \rho \left( \frac{d\Delta}{dt} \right) = S_{\text{paraboloid}} \rho \left( \frac{d\Delta}{dt} \right) = \frac{\pi R}{6h^2} \left[ (R^2 + 4h^2)^{3/2} - R^3 \right] \rho \left( \frac{d\Delta}{dt} \right) \]

**Turbulent**

\[ \Delta(t) \bigg| \frac{H}{H^*} = 1 - \left[ 1 + 0.082 \frac{H_\omega \pi R}{S_p} \left( Gr^* \right)^{2/7} \frac{1}{Pr^{2/7}} \phi^* \right]^{-7} \quad \Delta(t) \bigg| \frac{H}{H^*} = 1 - \left[ 1 - 0.616 \frac{H_\omega \pi R}{S_p} \left( \frac{Gr^*}{5 + Pr} \right)^{1/5} \frac{1}{Pr^{3/5}} \phi^* \right]^{-5} \]

\[ Gr^* = \frac{g\beta q_w \left( H + \frac{h}{2} \right)^4}{k \nu^2} = \frac{g\beta q_w (H_\omega)^4}{k \nu^2} \quad \phi = \frac{\nu t}{H^2_\omega} \]

Re-derive energy balance to take into account additional heating area

\[ \dot{q} 2\pi R \left( H + \frac{h}{2} \right) = \dot{q} 2\pi R H_\omega = \rho \pi R^2 \Delta c_p \frac{dT}{dt} \]
COMBINED ROTATION / STRATIFICATION MODEL: LH\textsubscript{2} and LOX

For q=10 W/m\textsuperscript{2}, L=3, R=1.5, 20\% fill level, H/R=0.4 and \(\omega=1^\circ/\text{sec}\) at \(g/g_0=10^{-4}\):

- Rotation decreases time to stratification time by \(~15\%\)
- Rotation increases stratification temperature by \(~1.0\ K\)
EFFECTS OF ROTATION AND TRADEOFFS

- Increased boundary layer running length ($H \rightarrow H_\omega$)
  - more heated area
  - larger Grashof number
- Larger surface area at bulk-stratum interface ($S \rightarrow S_{\text{parabolid}}$)
  - increased mass flow rate into stratum layer
  - more area to spread mass flow
EFFECTS OF ROTATION

- Spinning always increases stratification
- Stratum temperature affected by spin rate; especially at low gravity levels
- LOX cases shown with heat flux of 5 W/m² after 2 hour mission
EFFECTS OF ROTATION

- $\omega_{\text{critical}} \rightarrow$ spin rate to minimize stratum temperature
- $\omega_{\text{critical}}$ needed for large $g/g_0$ impractical
- $\omega_{\text{critical}}$ needed for typical mission profiles very practical ($\omega < 1.5$ deg/s)
- LOX results discussed previously shown

![Graph showing $\omega_{\text{critical}}$ vs. $H/R$ for $g/g_0 = 10^{-3}$ and $g/g_0 = 10^{-4}$]
SUMMARY/ CONCLUDING REMARKS

- Thermal stratification impacts T&P at conclusion of coast phase

- Rotation (creeping of fluid up side walls) has large effect for $\omega=1^\circ/s$ and $g/g_0=10^{-4}$
  - ‘Classical’ literature model upgraded to include rotation effects
  - Can decrease time to stratify by 30-60 minutes during 4 hour coast
  - Larger heating area and lower liquid level above sump inlet
  - For various missions stratum temperature may increases or decrease relative to no-spin case
  - Mixed tank temperatures always larger because $\Delta$ increased with rotation

- Future work
  - Comparison with CFD studies
SELECTED REFERENCES

Literature Review References:


Web-based References for Graphics:
- http://www.skyscraper.de/space/index_frame.htm
- http://www.skyscraper.de/space/doc_sdat/goes-n.htm

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