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

TFAWS Conference
NASA Glenn Research Center
2007

Florida Institute of Technology

NASA Kennedy Space Center

Department of Mechanical and Aerospace Engineering

Justin Oliveira
Daniel R. Kirk

Expendable Launch Vehicle / Mission Analysis Branch

Paul A. Schallhorn
Jorge L. Piquero
Mike Campbell
Sukhdeep Chase

2007 TFAWS
CONTENTS

• Project Overview

• Analytical Modeling

• Current Work

• Concluding Remarks

• Future Work
OVERVIEW: UPPER STAGE MODELING

Lockheed Martin
Atlas V 401

Boeing Delta IV Heavy


2007 TFAWS
OVERVIEW: WHAT CAN HAPPEN INSIDE TANKS?

- Stage exposed to solar heating
- Propellants ($\text{LH}_2$ 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
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
MISSION PARAMETER RANGES

- Tank Dimensions:
  - Square 3 m diameter tanks

- Cryogenics: LH$_2$, LOX
  - $T_{\text{bulk}}$ LH$_2$: 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$^2$

- 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
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

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

\[ \dot{q}2\pi RH = \rho \pi R^2 \Delta c_p \frac{dT}{dt} \]
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

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

$Ra = Gr \, Pr$

- 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

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

$Ra^* = Gr^* \, Pr$

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

- 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)

2007 TFAWS
WHAT IS IMPACT OF BBQ ROLL ROTATION:

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

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

- Does $1^\circ/\sec$ 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, $$\omega = 1^\circ/\text{sec}$$

$$\frac{g}{g_0} < 10^{-3}$$  $$\frac{g}{g_0} = 10^{-4}$$

$$\frac{g}{g_0} = 10^{-5}$$

Note: Parabola bottoms out
ROTATIONAL CASES

Re-examine boundary layer / stratum mass balance

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

**Turbulent**

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

**Laminar**

\[ \frac{\Delta(t)}{H_\omega} = 1 - \left[ 1 - 0.616 \frac{H_\omega \pi R}{S_p} \left( Gr^* \right)^{1/5} \frac{1}{Pr^{3/5}} \phi \right]^{5} \]

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

\[ \phi = \frac{\nu t}{H_\omega^2} \]

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

\[ \dot{q} 2\pi R \left( H + \frac{h}{2} \right) = \dot{q} 2\pi RH_\omega = \rho \pi R^2 \Delta c_p \frac{dT}{dt} \]
COMBINED ROTATION / STRATIFICATION MODEL: LH$_2$ and LOX

- For $q=10$ W/m$^2$, $L=3$, $R=1.5$, 20% fill level, $H/R=0.4$ and $\omega=1^\circ$/sec at $g/g_0=10^{-4}$:
  - Rotation decreases time to stratification time by $\sim 15\%$
  - Rotation increases stratification temperature by $\sim 1.0$ 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 ($S \rightarrow S_{\text{paraboloid}}$)
  - 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 the effects of rotation with $g/g_0 = 10^{-3}$ 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.boeing.com/defense-space/space/delta/delta4/d4h_demo/book01.html

2007 TFAWS