Upper Stage Tank Thermodynamic Modeling Using SINDA/FLUINT

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Outline

• Purpose/Overview
• Introduction
• Approach
• Fluid Sub-model Integration
• Required Inputs
• Stratification Modeling
• Rotation Modeling
• Slosh Modeling
• Conclusion
The purpose of this work is:

- Provide an independent modeling capability within NASA’s Launch Services Program for cryogenic upper stages

In this briefing, the following will be presented

- Describe the modeling approach employed
- Generic results to date
Introduction

• The NASA Launch Services Program’s Thermal/ Fluids team was tasked with developing a tool for future EELV mission IV&V activities

• This tool would allow for both thermal structural modeling as well as tank thermodynamics

• The desire to have a fully coupled thermal and fluids/thermodynamic modeling capability lead to the use of a commercially available software platform: SINDA/FLUINT

• The presentation specifically describes the fluids/thermodynamic modeling portion of the tool
Approach

Develop Thermal Conduction Model

Develop Thermal Radiation Model

Combined Thermal Model

Develop LH2 Tank Thermodynamic Model

Develop LOX Tank Thermodynamic Model

Combined Model

Run & Compare Baseline

Document Results

Scope of today’s discussion

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Approach

- Fluids/Thermodynamics Modeling – FLUINT
  - Fluid Conduction
    - Stratification
  - Convection
    - B/L development
  - Mass Transfer
    - Diffusion, vaporization & condensation
  - Boiling
  - Pressurization & Venting
  - Liquid Vapor Interface Area/Liquid Wall Interface Area during Rotation
Fluid Sub-model Integration

- **Fluid to Structure Integration**
  - TIEs are used to couple the thermal and fluid models
    - Analogous to SINDA conductors
    - Fluint lump to SINDA node energy interchange
    - Heat transfer coefficient can be inputted manually or automatically calculated by the program

- **Transient Integration**
  - Utilized S/F build commands to engage and disengage individual fluid sub-models to simulate discrete “events” along a continuous timeline
    - **Stratification**
    - **Rotation**
    - **Slosh**
  - Sequencing of “events” is controlled in OPERATIONS block and is dependant upon
    - Knowledge of mission being simulated
    - Identification of environments that signify the “event”
    - Use of multiple definitions of simulation completion times
    - Identification of variables necessary to maintain continuity between “events”
  - Thermo model may be run independently from the thermal model
Required Inputs

- Requires the input of various external data files
  - Mission Variables
    - Gravity
    - Rate of rotation (Passive Thermal Control Roll)
    - Vent schedule
    - CFD data relevant to fluid location within tank
  - Sub-routine files
    - Fluid depth
    - Liquid/vapor interface area and liquid/tank interface area
    - Boundary layer development
    - Natural convection
    - Boiling
Basic Overview of S/F

• SINDA
  • Nodes - Thermal mass
  • Conductors - Structural conduction path

• FLUINT
  • Lumps/tanks - Homogeneous fluid @ P & T
  • Twinned tank - Non-homogeneous tank
  • Paths - Momentum and energy balance

• Uncommon use of FLUINT (network code) to model fluid volume
Boiling Subroutine

Predicted Boiling Heat Flux For Various Values of Wall Superheat And Gravity (Oxygen, Vertical Surface, Pressures = 15, & 30 psia, @ 0.0001, 0.01 & 1. g.)

- All regimes of boiling and reduced gravity effects accounted for
• Development of a temperature stratum within a fluid largely due to buoyancy driven forces

• Model needs to account for
  – Energy and mass transport
  – Exhibit sufficient resolution to capture stratification
  – [Number of axial layers left to the discretion of the modeler]

• Model designed to accept
  – A direct heat flux input into the thermal nodes
  – A temperature difference between the wall and fluid
  – TIE’s coupling the fluid/thermo model directly with the thermal model

• Boundary layer subroutine provides
  – Local boundary layer thickness
  – Mass flow rates
Stratification (Continued)

- **TIEs** – Thermal to Fluids/Thermodynamic model coupler
- **FTIEs** – Fluid lump to lump conduction
- **MFRSETs** – Mass flow rate sets (calculated via boundary layer routine)
- **LOSS** – Generic two way fluid lump connector
- **SPO** – Connector for species specific diffusion in ullage
- **SUPER PATH** – handles mass transfer at liquid vapor interface
- **CTLVLV** – Used to control tank pressurization and depressurization

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Stratification Results

Percent of Bulk Fluid Thermal Stratification vs. Time For Various Values of Gravity (Liquid: Hydrogen, Oxygen and Nitrogen)

- Stratification was successfully modeled for various values of g
- Compared well to published data
Rotation – Event 2

- Development of the rotation model was motivated by the common occurrence of PTC roll in space/launch vehicles

- Model needs to account for:
  - Proper liquid/wall interface area
  - Proper liquid/vapor interface area
  - Development of “warm layer” or stratum
  - Proper mixing within fluid and ullage lumps

- PUTTIE routine
  - Dynamically moves TIEs as fluid comes in contact with hot wall areas

- Boiling subroutine
  - Accounts for any occurrence of boiling as the fluid comes into contact with hot walls that were previously adjacent to the ullage

- Data arrays provide a data base to determine liquid height and liquid/vapor interface area
  - Fill %
  - Rate of rotation (deg/s)
  - Gravity ratio (g/g<sub>c</sub>)
  - Data conforms to inputs provided by CFD simulations
• PUTIE routine dynamically moves the tie to the appropriate adjacent fluid or vapor lump as the fluid moves up the wall during a rotation event.
Rotation Results (Cont.)

LH2: Predicted Liquid Height at the Wall for Assumed Value of Vessel Rotation and Sloshing

- Rate of Rotation (deg/sec)
- Slosh (0=none, 1=Zone, 2=Nodal)
- Liquid Wall Height (ft)
- Liq/Vapor area (sq ft)

Wall Temperatures

- Wall @ 1.5 inches
- Wall @ 61.5 inches
- Wall @ 121.5 inches
- Wall @ 136.5 inches
- Ullage
- Wall @ 31.5 inches
- Warm Layer
- Bulk Liquid

Wall Temperature (DegR)

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Slosh – Event 3

- Development of the slosh model was motivated by the interest in potential effect on tank pressure (ullage collapse) and liquid boil-off
- Slosh fluid network is very similar to the rotation event
- The chaotic nature of the event precludes a high fidelity model
- Slosh also utilizes the PUTTIE routine
- Boiling subroutine
- Two levels of fidelity available to user
  - Zone (clusters of SINDA nodes) wetting
  - Individual SINDA node wetting
- CFD analysis provides intelligent input for conjugate modeling
Slosh (Continued)

8 radial, 56 vertical segments

- Tank Nodal breakdown can also be clustered into zones (white/green) for the slosh routine

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Slosh Results – Zone Slosh

- TIES stay connected to thermal node. They switch from liquid to ullage and vise versa

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Slosh Results – Node Slosh

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Conclusion

- Tool has been successfully developed for use in predicting upper stage propellant thermodynamics
- Achieved full thermal-fluids coupling using commercially available SINDA/FLUINT
- Event models can run concurrently
- The tool set will form a foundation for future NASA LSP analysis efforts
- The suite can be easily adapted for
  - EELVS fleet
  - CLV, CaLV and CEV
  - Commercial applications (any fluid, any tank)
Questions?
Boundary Layer Development
Results

in conjunction with the aforementioned oral presentation.
Modeling with Twinned Tanks
Rotation Results (Cont.)

Assumed Conditions: 20% of available dry wall is splashed at slosh, $g/g_c = 10^{-4}$
Period = 2.5 Hours, 1400 lbs liquid, Tank Fill Level ≈ 22% (Full = 1496 cu. Ft.)
Initial Conditions: Wall Temperature = Sat + 100 °R,
$P = 19$ psia, Liquid Temperature = 37.5 °R, Ullage Temperature = Sat +10 °R

Valve Seat Pressure

Valve Crack Pressure

Tank Pressure

Rotation Rate

Slosh (0=None, 1=Zone, 2=Nodal)