Ablation Modeling of a Solid Rocket Nozzle

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Overview

Castor 30® motor description
Ablation model
CFD (Fluent®) modeling for boundary conditions
Hero ablation modeling
FEM Builder model coupling
Modeling results
FEM Builder coupling capabilities
On-going work
CASTOR 30

VECTORIZABLE NOZZLE IN-LINE UPPER STAGE BOOSTER

The CASTOR 30 is a low cost, robust, state-of-the-art upper stage motor. This development motor is 138 in. long and nominally designed as an upper stage that can function as a second or third stage depending on the vehicle configuration. The design of the CASTOR 30 uses all flight proven technology and materials.

MOTOR DIMENSIONS
Motor diameter, in.......................... 92
Motor length, in.............................. 138

MOTOR PERFORMANCE (73°F VACUUM)
Burn time, sec.................................. 143
Average chamber pressure, psia.............. 762
Total impulse, lbf⋅sec.......................... 8,34M
Web time average thrust, lbf.................. 58,200

NOZZLE
Housing material.............................. Aluminum
Exit diameter, in............................. 47.5
Expansion ratio, average..................... 50

WEIGHTS, LBM
Total loaded.................................... 30,998
Propellant...................................... 28,300
Case............................................. 899
Nozzle/igniter/TVA............................ 748
Other............................................ 1,051

TEMPERATURE LIMITS
Operation........................................ +30°-100°F

PROPELLANT DESIGNATION
Modified TP-H8299, HTPB polymer, 20% aluminum

PRODUCTION STATUS........................ In-design
Ablation Model (In-Depth)

• **Pyrolysis**

\[
\frac{d\rho_s}{dt} = -(\rho_v - \rho_c) \frac{\partial \alpha}{\partial t}
\]

rate of solid density change

\[
\alpha = \frac{\sum x_i \alpha_i}{\sum x_i}
\]

overall versus component extent-of-reaction

\[
\frac{\partial \alpha}{\partial t} = \frac{\sum \frac{\partial \alpha_i}{\partial t}}{\sum x_i}
\]

overall pyrolysis rate

\[
d\alpha_i = A_i e^{(-E_{a,i}/RT)} (1 - \alpha_i)^{n_i}
\]

Arrhenius model for component extent-of-reaction

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- **Mass/Momentum Equation**

\[
(\rho_v - \rho_c) \frac{\partial \alpha}{\partial t} + \nabla \cdot \left( \frac{\hat{\rho}_g}{\mu_g} \Gamma \nabla P \right) - \hat{\rho}_g (\phi_c - \phi_v) \frac{\partial \alpha}{\partial t} = 0
\]

generation advection (permeation) storage

- Neglected storage (quasi-steady)

\[
(\rho_v - \rho_c) \frac{\partial \alpha}{\partial t} + \nabla \cdot \left( \frac{\hat{\rho}_g}{\mu_g} \Gamma \nabla P \right) = 0
\]

generation advection (permeation)

- 1-D simplification (with neglected storage)

\[
\hat{m}_g''(x_p) = -\frac{1}{A} \int_{x_p}^{x_b} A \frac{\partial \rho_s}{\partial t} dx
\]

**Energy Equation**

\[
(Q_s - h_s + h_g) (\rho_v - \rho_c) \frac{\partial \alpha}{\partial t} + \hat{\rho}_g \phi \frac{\partial h_g}{\partial t} + \rho_s \frac{\partial h_s}{\partial t} = 0
\]

pyrolysis energy storage advection conduction

\[
\hat{\rho}_g v_D \cdot \nabla h_g - \nabla \cdot K \nabla T = 0
\]
Ablation Model (Surface Model)

- **Unity Lewis number**
  \[ q''_{\text{cond}} = \rho u C_H \left[ H_r - (1 + B') h_w + B'_c h_c + B'_g h_g \right] + \alpha_w q''_{\text{rad,inc}} - \varepsilon \sigma T_w^4 \]

- **Equal diffusion coefficients**
  \[ q''_{\text{cond}} = \rho_u C_H \left( H_r - h_w \right)_{f.e.g} + \rho u C_M \left[ \sum K_{i e} - \sum K_{i w} \right] h_i^{T_w} + B'_c h_c + B'_g h_g - B'h_w \] + \alpha_w q''_{\text{rad,inc}} - \varepsilon \sigma T_w^4

- **Unequal diffusion coefficients**
  \[ q''_{\text{cond}} = \rho u C_H \left( H_r - h_w \right)_{f.e.g} + \rho u C_M \left[ \sum Z'_{i e} - \sum Z'_{i w} \right] h_i^{T_w} + B'_c h_c + B'_g h_g - B'h_w \] + \alpha_w q''_{\text{rad,inc}} - \varepsilon \sigma T_w^4

- **Surface ablation rate**
  \[ \dot{s}_{\text{chem}} = \frac{\dot{m}_c}{\rho_c} = \frac{B'_c \rho_u C_M}{\rho_c} \]

**Thermochemistry**

- "B-prime" tables from ACE code

**Heat transfer coefficients from CFD modeling**
**CFD Modeling (Approach)**

- 2D axi-symmetric, steady state, 2-phase, non-reacting CFD model
- Simulated 0.6, 15, 30, 45, 60, 75, 90, 105, 120, 135 sec burn times
- Propellant mass flow rate adjusted to match measured chamber pressure
- Gas properties from NASA Lewis chamber properties at appropriate pressures, frozen chamber $C_p$ and molecular weight, temperature dependent thermal conductivity and viscosity
- K-Omega, SST turbulence model, $y^+$ values 30-100
- 34.6 wt% $\text{Al}_2\text{O}_3$ liquid at equilibrium
  - 24% large agglomerates, sizes from quench bomb data (40-300 microns)
  - 76% fines
- ATK droplet breakup model with size dependent critical Weber number
Hero Ablation Modeling (Overview)

- 81,092 elements (1\textsuperscript{st} order)
- Heat transfer, pyrolysis, pore pressure, thermochemical surface ablation
- 0 – 155 sec
  - $\Delta t = 0.01$ through 1.5 sec
  - $\Delta t = 0.05$ through 155 sec
Hero Ablation Modeling (Grid Details)
FEM Builder Model Coupling

- Initial boundary conditions calculated in Fluent and imported into Hero using FEM Builder (~ 0 sec)
- Hero run for 15 sec (boundary conditions modified within Hero based on transient pressure)
- Eroded surface (at 15 sec) imported into Fluent
- Boundary conditions recalculated
  - Eroded surface
  - Propellant burn-back
  - Imported into Hero
- Process repeated in 15 sec interaction intervals through 155 sec
Temperature Contours of Full Nozzle
Modeling Results (Contours of Temperature and Char)

Temperature Contours in Throat Region

Extent-of-Reaction (Char) Contours in Throat Region
Modeling Results (Animated)

0 – 155 sec

15 – 30 sec
FEM Builder Coupled Fluid-Thermal-Structural Interaction Analysis

Solutions type/Time domain
- CFD – Quasi steady
- Heat transfer – Transient
- Structural – Quasi steady

CFD – Structural Interactions
- Pressure on structure
- Displacement of CFD boundary

CFD – Thermal Interactions
- Surface temperature for CFD model
- Heat flux from CFD model
- Ablation from thermal model (modifies CFD boundary)
- Particle impingement (Slag)

Thermal – Structural interactions
- Temperature is applied to the structural model
- Pore pressure (causes stress & permeability is strain dependent)
- Deformation of thermal model

Reference models
CFD models
Thermal models
Structural Models

Model Coupling Capabilities

Flow/Structural Coupling Example
On-going Work

- CFD 2-phase reacting flow
- Conjugate CFD/ablation modeling
- Grain burn-back modeling
- Additional GUI (FEM Builder) support for generation of coupling scripts
- Surface thermochemistry code development
- Slag impingement heating and erosion modeling
- Comprehensive validation against historical data
- Improved material property characterization methods
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Program availability

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