Developing a Pyrolysis Gas Thermal Blocking Model for Reentry Demise

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Modeling Reentering Debris

- **NASA uses the Object Reentry Survival Analysis Tool (ORSAT)**
  - **Spacecraft modeled as a collection of nested components**
  - **Each component is released on its own independent trajectory when the parent component demises**
  - **“Demise” occurs when a fragment absorbs enough thermal energy to completely melt or vaporize**
  - **For traditional aerospace materials like titanium or aluminum, this model works well**

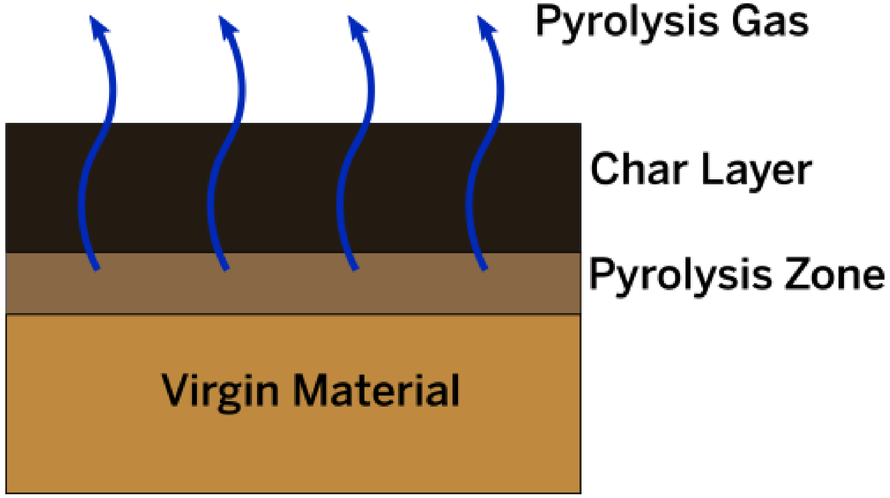
Introduction

- Fiber-reinforced polymers (FRP) pose unique challenges to reentry ground casualty risk assessment
  - Polymer matrix pyrolizes before fiber material melts
  - Char matrix can have enough shear strength to hold the component together through reentry
  - Charred material stays intact and acts as thermal barrier to further charring
  - Gaseous pyrolysis products are expelled through the surface, reducing the input heat flux through transpiration cooling

Pyrolysis Gas Surface Blowing

Char process

- Pyrolysis occurs as material reaches its pyrolysis temperature (400 – 600 K)
- Pyrolysis zone recedes into material as heat is conducted
- Pyrolysis products are expelled through porous char layer
  - Transfer heat from char layer into pyrolysis products
  - Mix thermal energy back into the boundary layer



- Char surface ablates through one or more of several processes
  - Chemical erosion by oxidation and nitridation reactions
  - Melting of fiber reinforcement
  - Aerodynamic erosion & spallation

Effects of Pyrolysis Gas on Heat Flux/Recession

Convective Cooling

- Pyrolysis products at ~500 K, surface of char at ~1000 K

Bulk displacement of high-temperature flow

- Layer of relatively cool fluid insulates surface from convective transfer with free stream

Chemical depletion of free oxygen in boundary layer

- Oxidization typically drives recession rate of char layer
- Oxidation can also contribute to surface heat flux
- Simple hydrocarbons in pyrolysis products react with free oxygen radicals, reducing availability of oxygen at the char surface

Soot generation in boundary layer

- Reduce radiative transmissibility of boundary layer
- Soot particles have elevated temperature from combustion, which can radiate to the surface

Thermal Blocking Models

- **Blowing parameter correlations**
  - B', ratio of pyrolysis and ablation mass flux to freestream mass flux
  - Ψ, ratio of surface heat flux to theoretical hot-wall heat flux
  - Correlate thermal blockage factor, Ψ, with blowing parameter, B', from empirical data and simulation
  - Simplistic model
  - Tends to be applicable to only narrow range of conditions
- **Film Theory**
  - Correlation of boundary layer Reynolds, Stanton, and Prandtl numbers
  - Still relies on empirical data and simulations
- **Numerical Simulations**
  - Directly model chemical reaction rates and boundary layer flow

ORSAT Implementation

- **Model input values**
  - Mass flux of pyrolysis products (from FRP pyrolysis model)
  - Free-stream mass flux (from trajectory model)
  - Post-shock O, O2, N, and N2 number densities (from Fay-Riddell model)
  - Re, Nu, St, and Pr based on body characteristic length, approximate values for fluid thermal conductivity
- **Assumptions**
  - Chemical equilibrium composition of pyrolysis products
  - Composition of pyrolysis products (based on published studies)
  - Number densities of O, O2, N, and N2 at wall are equal to chemical equilibrium values in mixture of pyrolysis products and post-shock flow
  - Average actual heat flux is equal to a blocking factor multiplied by the calculated hot-wall heat flux
- **Basic Process**
  - Calculate effective heat flux based on Re/Nu/St correlations
  - Calculate number density of O, O2, N, and N2 at wall and use reaction rates with surface char to estimate a surface recession rate

Implementation Progress

1. Identify published studies for model development and validation data
2. Develop model framework and equations
3. Perform numerical simulations and use data from published studies to correlate the blowing parameter to the thermal blocking factor
4. Implement model equations in ORSAT code base
5. Run validation studies comparing with published data

QUESTIONS/COMMENTS