Ablator Modeling: Why Not Much Has Changed Over the Past 45+ Years

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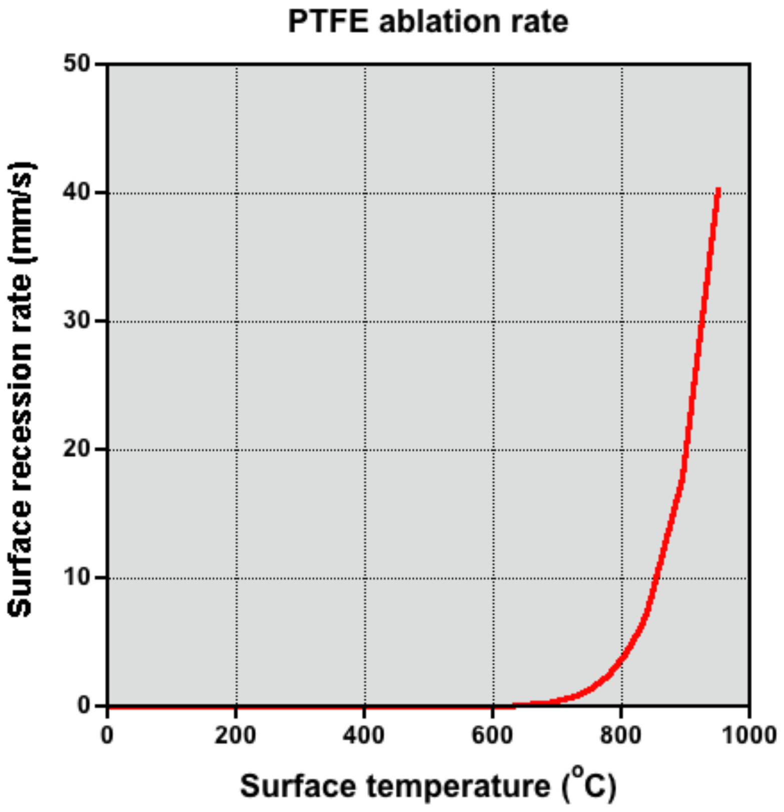
Outline

- Chronology
  - Early approaches to ablation modeling
  - Adoption of industry standard
- Constraints to further development
  - Not many new materials
  - Benefits vs. costs
- Modeling Enhancements
  - Addressing specific issues
- What’s the payoff?

Early models

- Because teflon ablates over a very narrow surface temperature range, early models (late 50s-early 60s) were *constrained* by the concept of an “ablation temperature”
- This led to the development of the “heat of ablation” concept which is poorly understood and typically misapplied
- The “heat of ablation” (Q*), is often referred to as a material “property.” It is not a *property* – it is a data correlation parameter that is only valid at **steady-state ablation conditions**.



What is the Heat of Ablation?

- The *thermochemical heat of ablation*, defined below, was calculated from the results of each arc jet test and plotted vs. $\left(H_r - H_{air}^{T_w}\right)$

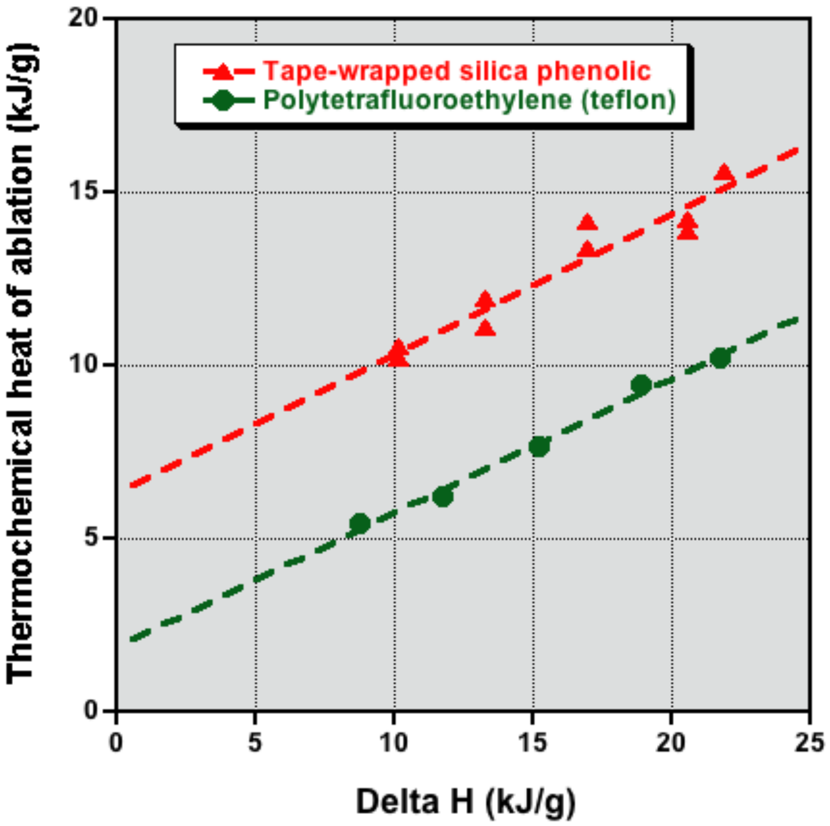
$$Q^* = \frac{\dot{q}_{cw}\left(\dfrac{H_r - H_{air}^{T_w}}{H_r}\right) - \sigma\varepsilon T_w^4}{\rho\dot{s}} = c_p\Delta T + \Delta H_v + \eta\Delta H$$

A linear fit through the data produces a line whose slope is taken as η and whose y-intercept is taken as $c_p\Delta T + \Delta H_v$. Since c_p and ΔT are known or were determined in the test, one also derives ΔH_v from the linear fit of the data.

Heat of Ablation Correlations

Entry Systems & Technology Division *Entry Systems & Vehicle Development Branch*

- Example:[†]
  - Tape-wrapped silica phenolic (ρ = 1.63 g/cm^3)
  - PTFE (ρ = 2.18 g/cm^3)
  - Tests in Avco's Model 500 arc jet (circa 1965)
  - Flat-faced stagnation samples in air
  - Cold-wall heat fluxes in the range from ≈ 0.7-1.5 kW/cm^2



[†] "Ablation Handbook, Entry Materials Data and Design," AFML-TR-66-262, September 1966.

More Advanced Modeling

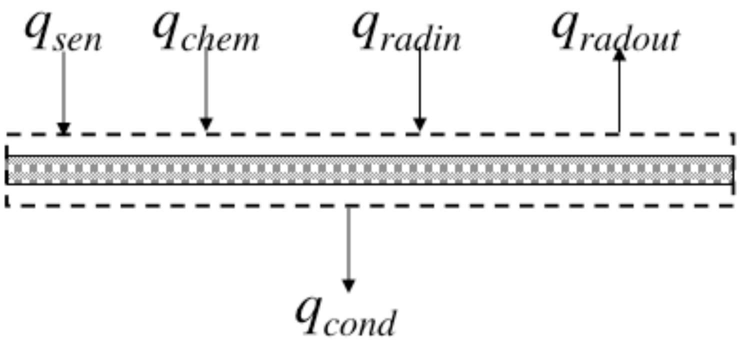
- Earliest model of in-depth thermal response for an organic resin composite was developed by Munson & Spindler[1] (Avco, 1962)
  - Included Arrhenius relation for decomposition kinetics
  - Surface recession primarily modeled via empirical correlation
- A more rigorous, chemical modeling approach was introduced by Kratsch, Hearne & McChesney[2] (Lockheed, 1963)
  - Modeled the composite as a mixture of organic resin and reinforcement (organic or inorganic), i.e.,

$$\rho_s = \Gamma \rho_{resin}(T,\theta) + (1-\Gamma)\rho_{reinf}(T,\theta)$$

where Γ is the resin volume fraction.

Thermochemical surface models

- Kratsch, Hearne & McChesney adopted a transfer-coefficient approach (developed by Lees[4]) for approximating the heat transfer to an ablating surface from a chemically-reacting boundary layer



$$\underbrace{\rho_e u_e C_H \left(H_r - h_{ew}\right)}_{q_{sen}} + \underbrace{\rho_e u_e C_M \left[\sum_i \left(Z_{i_e}^* - Z_{i_w}^*\right) h_i^{T_w} - B' h_w \right] + \dot{m}_c h_c + \dot{m}_g h_g}_{q_{chem}}$$

$$+ \underbrace{\alpha_w q_{rad}}_{q_{radin}} - \underbrace{F \sigma \varepsilon T_w^4}_{q_{radout}} - q_{cond} = 0$$

Industry Standards

- Kendall, Rindal and Bartlett[5] (Aerotherm, 1967) extended the work of Kratsch, Hearne & McChesney under contract to NASA JSC
  - One-dimensional thermal/ablation response of the charring ablator *fully coupled* to the non-similar, chemically reacting boundary layer (CABLE)
  - Bifurcation approximation for diffusion coefficients extended the formulation to cases of unequal diffusion coefficients and Pr≠Le≠1.0
  - Corrected energy equation to account for energy associated with surface recession

$$\rho c_p \left.\frac{\partial T}{\partial \theta}\right)_x = \frac{1}{A}\frac{\partial}{\partial x}\left(kA\frac{\partial T}{\partial x}\right)_\theta + \left(h_g - \bar{h}\right)\left.\frac{\partial \rho}{\partial \theta}\right)_y \left.\frac{\dot{m}_g}{A}\frac{\partial h_g}{\partial x}\right)_\theta + \dot{s}\rho c_p \left.\frac{\partial T}{\partial x}\right)_\theta$$

- Under USAF sponsorship, separated CABLE into three standalone codes that became industry standards (1970)
  - **BLIMP**: Non-similar chemically-reacting boundary layer code
  - **CMA**: one-dimensional charring ablation code
  - **ACE**: chemical equilibrium code (treated open systems, i.e., produces thermochemical equilibrium solutions of B' for any chemical system (with limited capability to treat reaction-rate limited chemistry)

Constraints on Further Development

- Models for the ablative materials of interest were developed and *validated* in the late 60s-mid 70s
  - Not many new ablative materials being developed
  - NASA shifted attention to reusable TPS (Shuttle)
- TPS designs were successful
  - Further modeling improvements could potentially provide relatively small improvements in TPS mass
  - Data requirements to support such modeling advancements would require significant investment
- Cost-benefit analysis not favorable

Modeling Enhancements

- Since CMA was made widely available in 1970, there have been several modeling improvements developed within the industry, including:
  - FIAT – converted CMA's explicit pyrolysis logic to implicit and redesigned the code for TPS sizing
  - Several 1-D finite volume and finite element codes developed
  - 2-D (e.g., TITAN) and 3-D codes (e.g., TRAPS) developed (same basic modeling as CMA/FIAT)
  - Addition of transient momentum equation or D'Arcy Law (steady-state) to calculate in-depth pore pressure due to pyrolysis
  - Addition of models to predict char spall (thermal and pressure stresses)
  - Addition of models to predict particle impact erosion (empirically-based)
  - Addition of logic to calculate surface thermochemical ablation as part of thermal response (eliminates requirement for B' tables)
  - Recent efforts to couple thermal/ablation response to CFD (e.g., FIAT/DPLR)
  - Recent efforts to calculate pyrolysis gas chemistry with reaction kinetics

Current & Future Efforts

- Significant interest in community to develop/introduce models for:
  - Pyrolysis gas and surface ablation chemistry governed by reaction kinetics
  - Surface catalysis
  - Coupling surface ablation chemistry with CFD
  - Surface roughness and mass injection effects
  - In-depth radiation transport
  - Others?
- Issues:
  - Acquiring the data necessary to support model development and validation requires sophisticated experiments and diagnostics
  - The number and availability of test facilities (e.g., arc jets) capable of simulating environments of interest is very limited
  - The potential for model validation with data from instrumented flight experiments is highly unlikely
- Acquiring the resources ($$$) to support advanced model development will require a favorable cost-benefit demonstration