The Melting Ablation Analysis of Meteorites in High Temperature Flow

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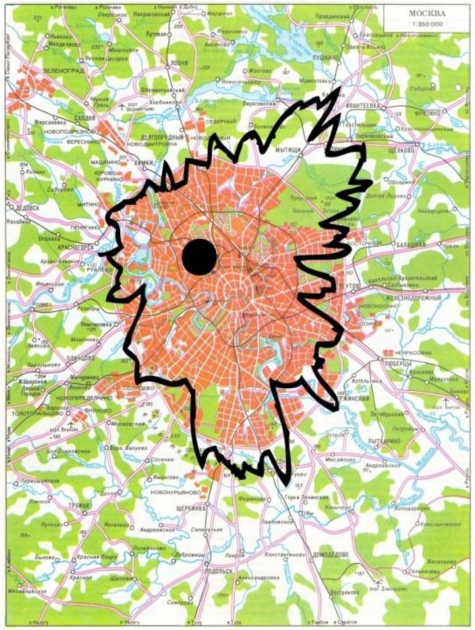
1. Background



Tunguska event, Russia, 1908 , ~70m, ~15km/s

Chelyabinsk event, Russia, 2013, ~20m, ~19km/s

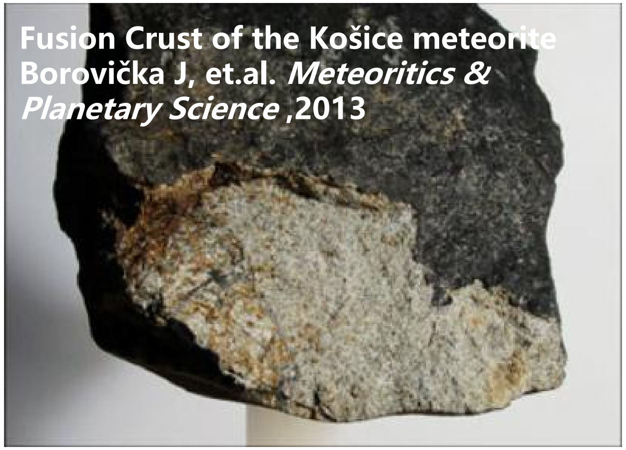
K/T event, Chicxulub, Mexico, 65 millions years ago, extinction of dinosaurs, ~10km, ~14km/s

1. Background

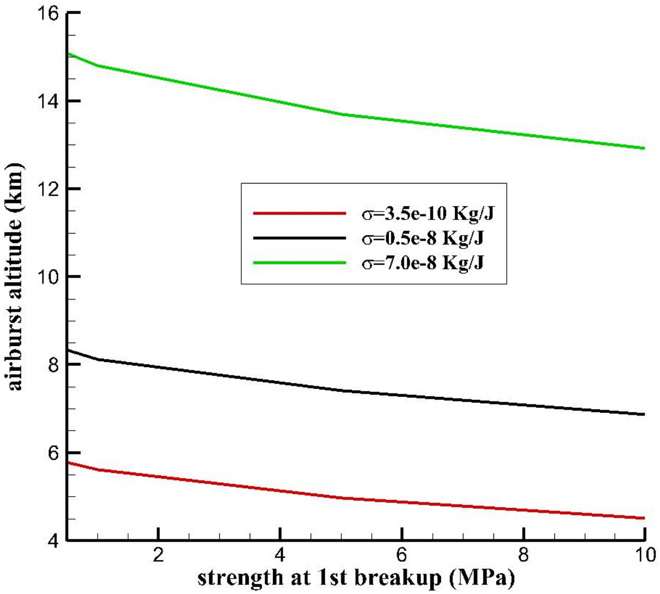
- Ablation of meteoroid caused by aerodynamic heating leads to massive mass loss, affects trajectory and radiation characteristics during Earth entry with hypervelocity speed .
- Ablation coefficient of meteoroid is under large uncertainty , and gives rise to unfavorable effects in risk assessment.

 range: 3.5×10^{-10} - 7×10^{-8} kg/J

- Aiming to reveal mechanism and predict ablation of meteoroid, ground experiments, modeling and computation had been carried out by NASA, VKI, University of Stuttgart, et. al.
- The preliminary work in this field by CARDC will be presented in this paper.



Fusion Crust of the Košice meteorite
Borovička J, et.al. *Meteoritics & Planetary Science* ,2013

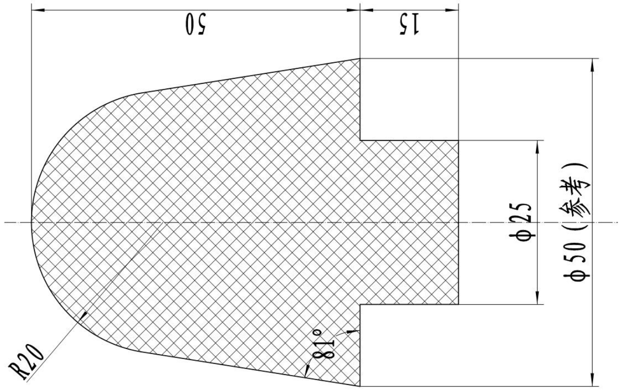


Dang Leining, et.al. Chinese Journal of Theoretical and Applied Mechanics,2020.12

2. Introduction to the Experiments at CARDC

Meteorite material

- NWA 13132, 2007, Niger, Northwest Africa
- Ordinary chonrite (L5/6)
- The meteorite is mainly consisting of olivine, pyroxene, plagioclase, Fe-Ni metal, with minor chromite and phosphates.

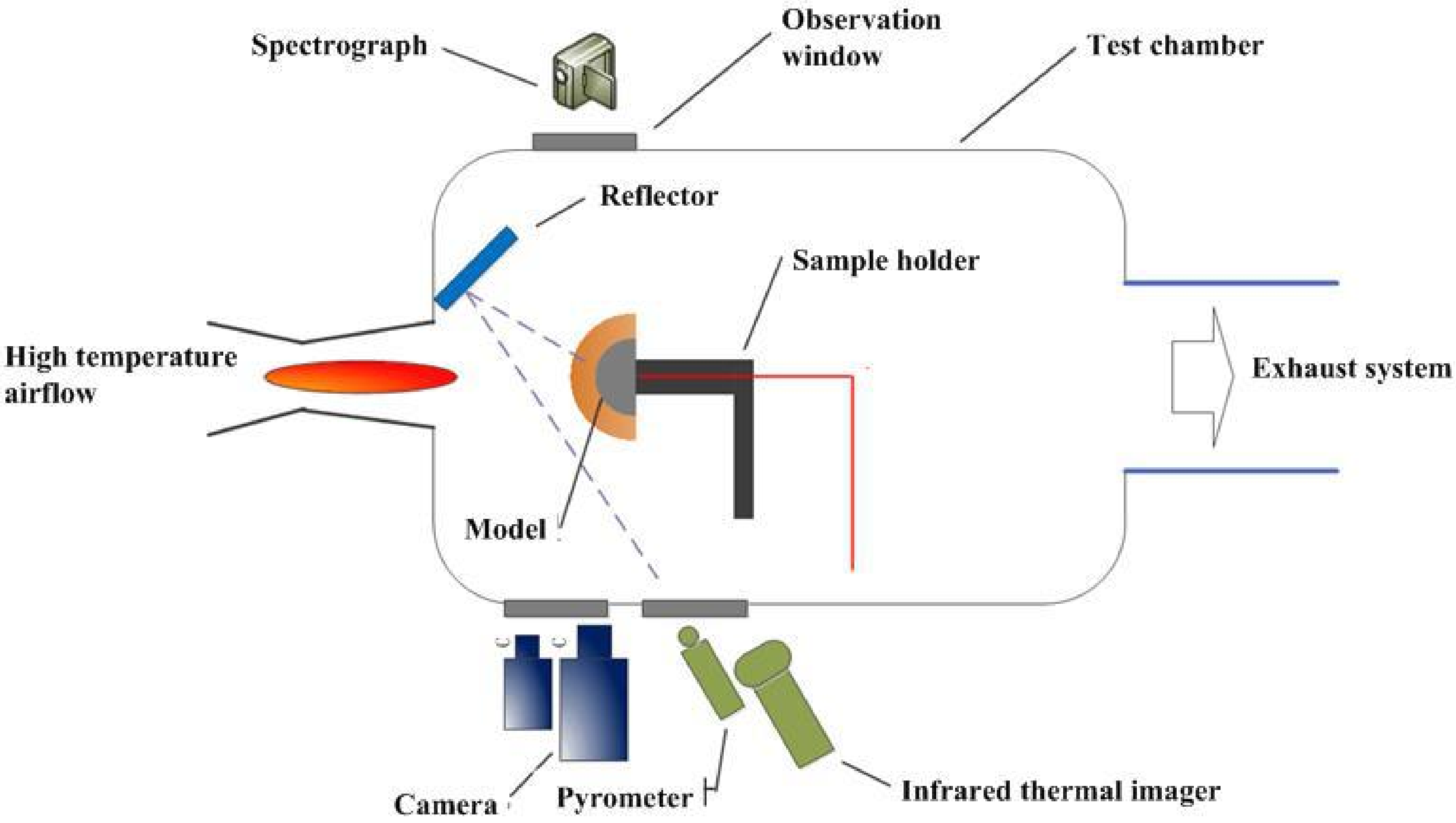


The test model

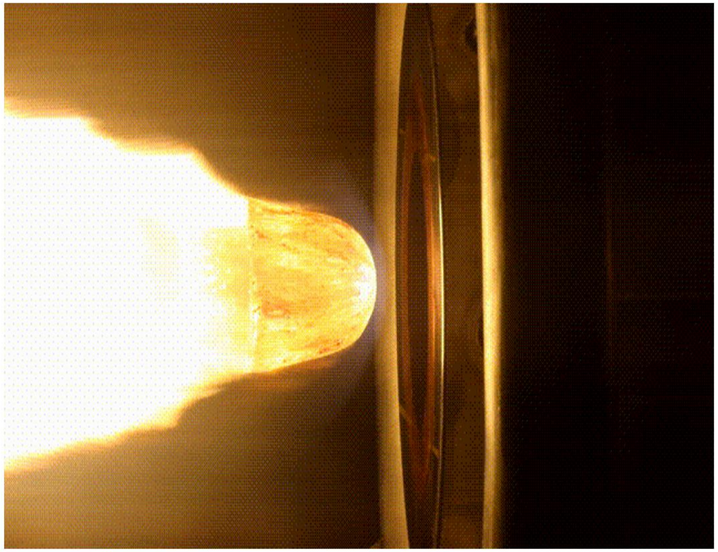

The raw meteorite material

State	I
Enthalpy (MJ/kg)	7.7
Stagnation heat flux (MW/m^2)	13.1
Stagnation Pressure (MPa)	0.51

- Experiment facility: 20 MW arcjet wind tunnel at CARDC



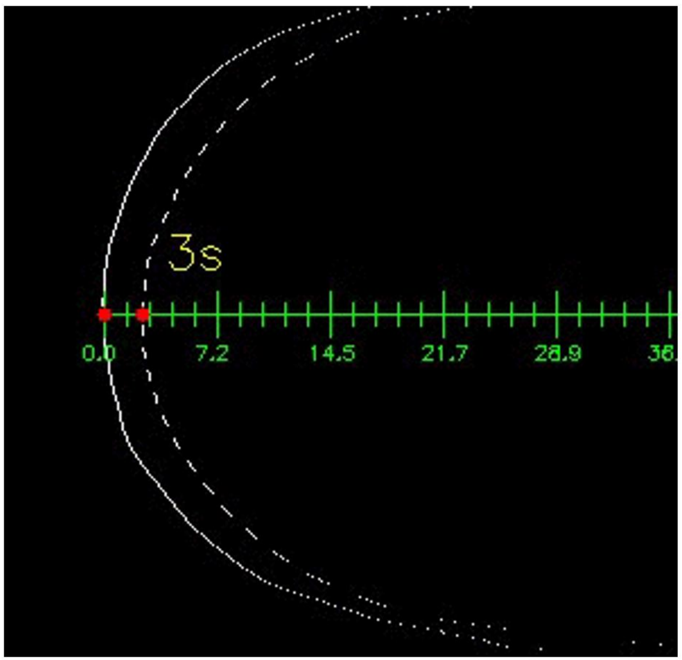
Sample #4 of Stony meteorite



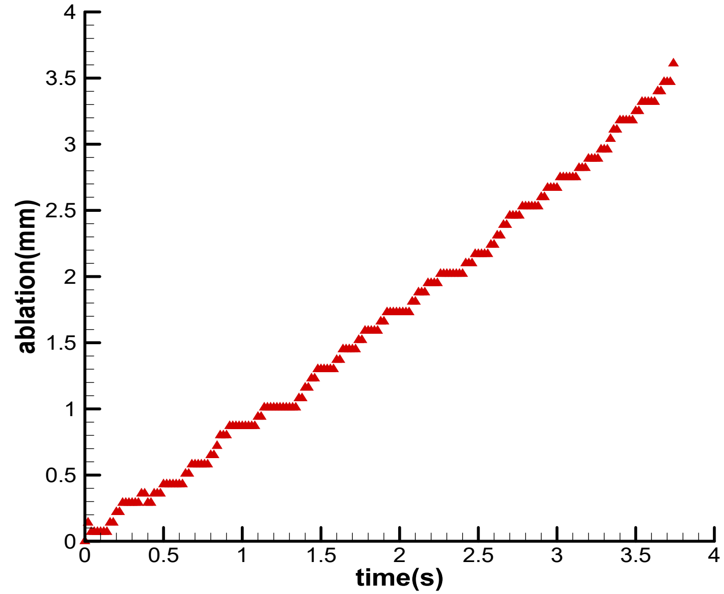
Melt flow over stony meteorite model during arc-jet exposure

The posttest shape (Sample #4)

Sample #4 of Stony meteorite



The ablation shape change during the experiment



The surface recession with time at the stagnation

1. Background
2. Introduction to the Experiments at CARDC
3. **Description of Melting Ablation Model**
4. Results and Conclusions

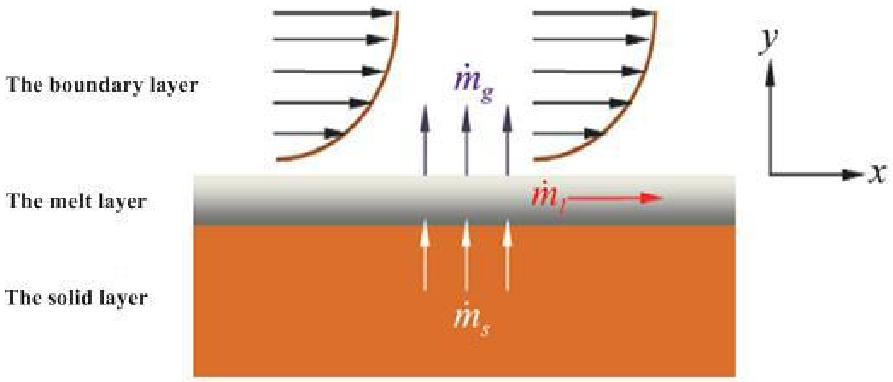
3. Description of Melting Ablation Model

■ The main phenomena

1. The heat conduction in the solid region
2. The energy taken off by the motion of the melt layer;
3. The latent heat absorbed during the evaporation process;
4. The thermal blocking effect induced by the sio_2 injected into the boundary layer.

■ The assumption of Model

1. Steady state;
2. Incompressible flow;
3. Inertia term is ignored in the momentum equation;
4. The transverse temperature gradient is ignored in the energy equation.



Melting Ablation Mode

Evaporation rate

$$\mathrm{SiO_2(l)} \rightarrow \mathrm{SiO_2(g)}$$

$$\mathrm{SiO_2(g)} \rightarrow \mathrm{SiO_2} + \frac{1}{2}\mathrm{O_2}$$

$$p_s = p_0 \exp\left(18.48 - \frac{57780}{T_w}\right)$$

$$C_w = \left[1 + M_{av}\left(\frac{P_e}{P_s} - 1\right)\right]^{-1}$$

$$\dot{m}_v = \left(\frac{C_w}{1 - C_w}\right)\left(\frac{\varphi q_{or}}{h_r}\right)$$

Equations of steady state liquid layer

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

$$\frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) = \frac{dp}{dx}$$

$$v\frac{\partial T}{\partial y} = \frac{k_l}{\rho_l c_{pl}} \frac{\partial^2 T}{\partial y^2}$$

$$\mu = \exp\left(\frac{a}{T} - b\right)$$

stagnation:

$$v_w - v_{-\infty} = -\frac{2\delta^2}{\mu_w}\left(\tau_w^{'} - 2p^{''}\delta\right)$$

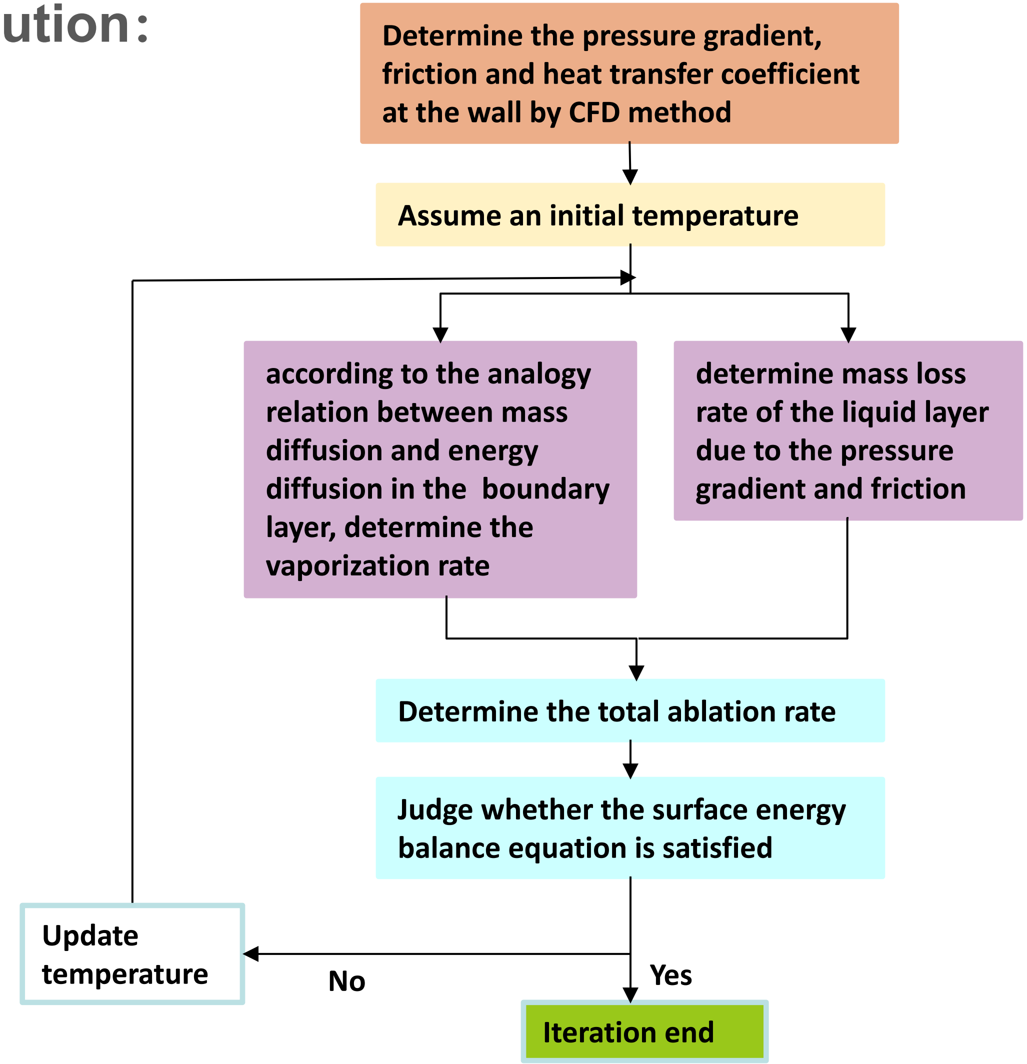
other zone:

$$\int_0^x \left(v_{-\infty} - v_w\right) r dx = r\frac{\delta^2}{\mu_w}\left(\tau_w - 2p_x\delta\right)$$

*Bethe H, Adams M C. A Theory for the Ablation of Glassy Materials. Journal of the Aerospace Sciences,1959

3. Description of Melting Ablation Model

Flowchart of solution:



3. Description of Melting Ablation Model

■ Validation: Fused Silica at NASA Ames

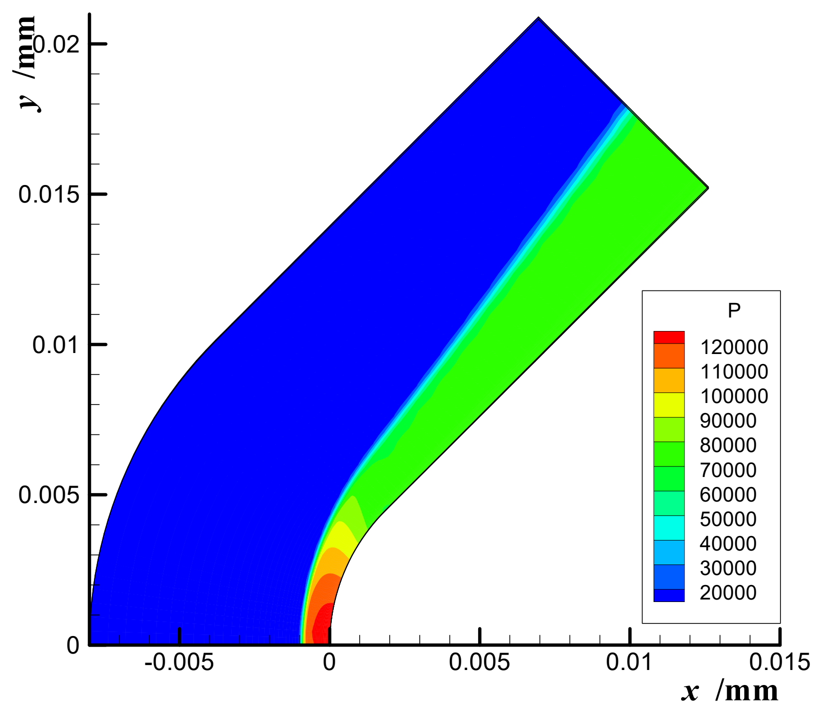
- ➢ Fused Quartz test article
- 45 deg sphere cones
- 1.524 cm depth
- 0.635 cm nose radius
- 3.07 cm base diameter

- ➢ State
- stagnation pressure 126kPa
- stagnation heat flux 3350W/cm2
- Enthalpy 20.6MJ/kg
- exposure time 2.66s

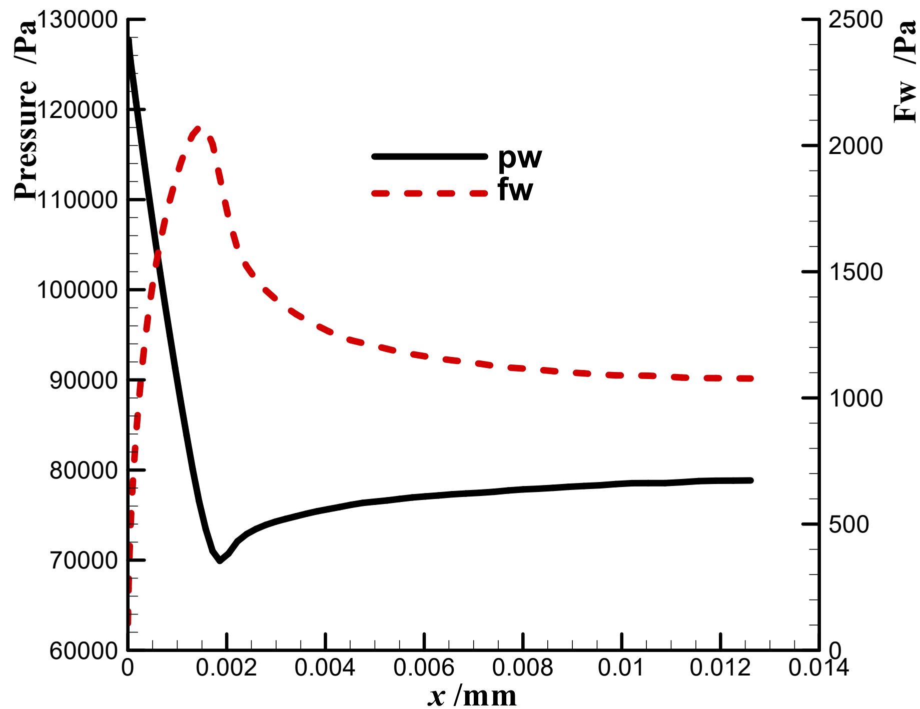
Yih-Kang Chen, Eric C Stern, Parul Agrawal. Thermal Ablation Simulation of Quartz Materials. Journal of Spacecraft and Rockets, 2019

3. Description of Melting Ablation Model

■ Validation：CFD Result



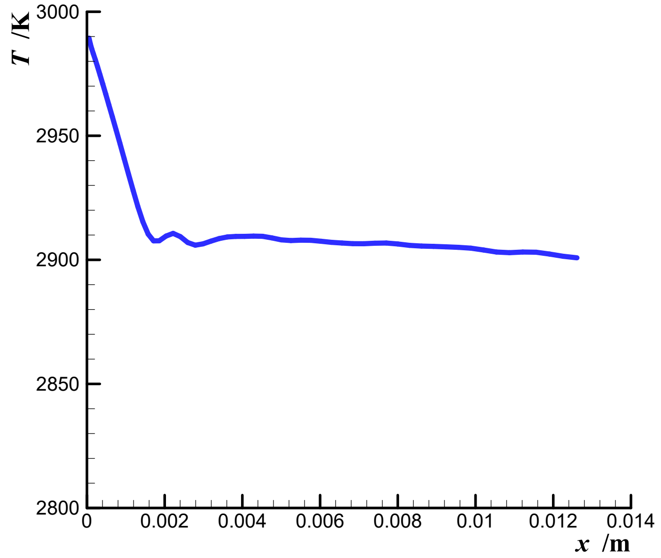
The pressure field



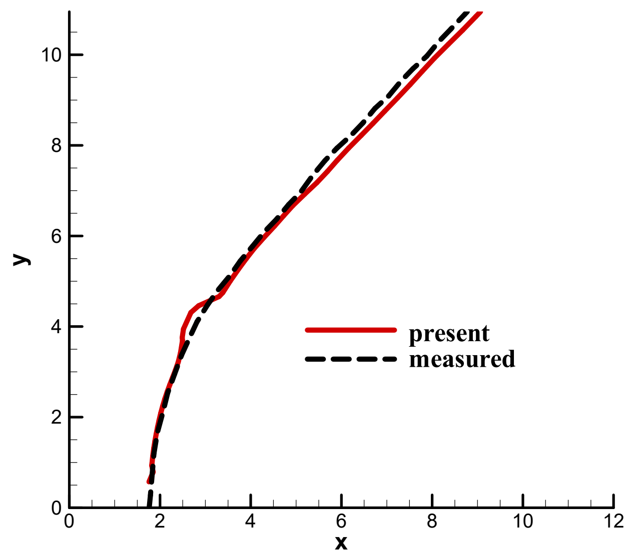
The pressure and wall friction distribution along the x-axis

Validation: Ablation Results

The ablation recession rate: 0.662mm/s

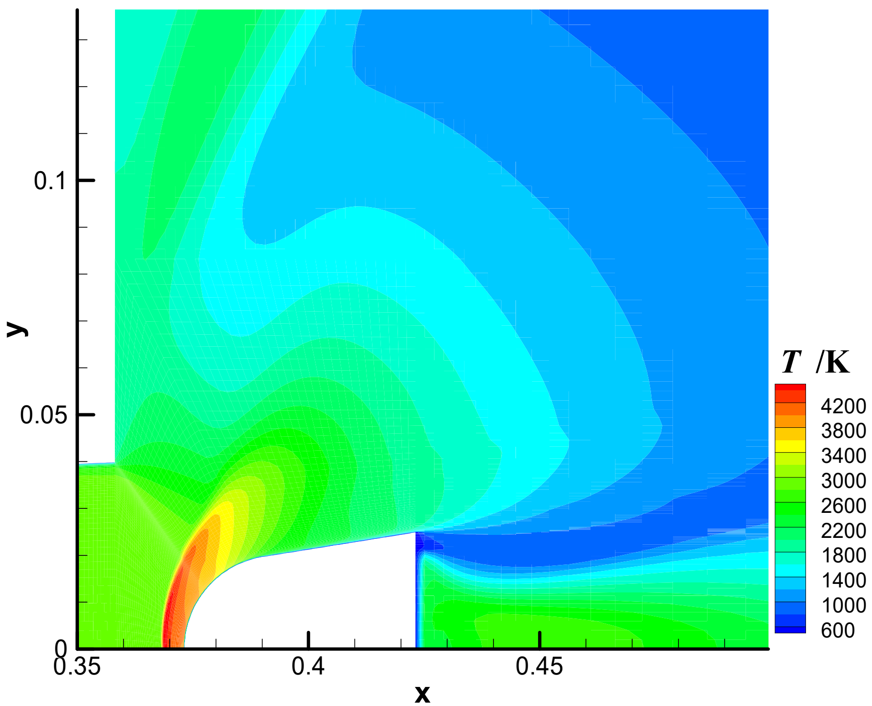


The surface temperature distribution

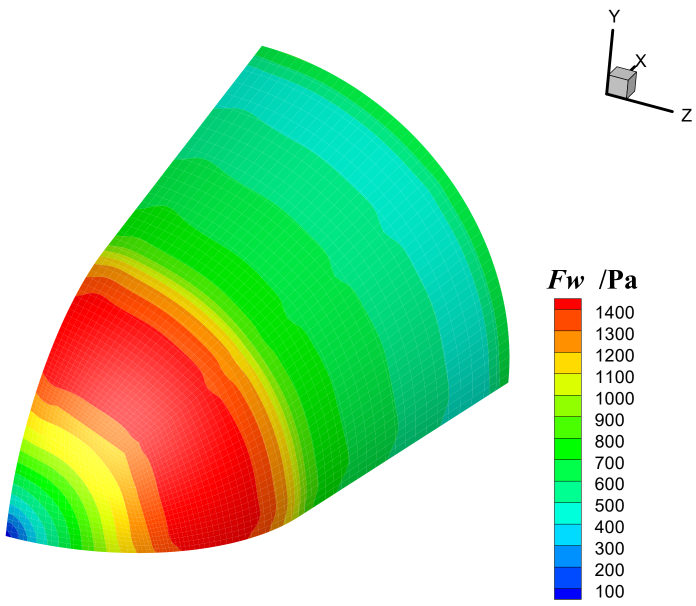


The posttest ablation shape at 2.66s

The CFD Results

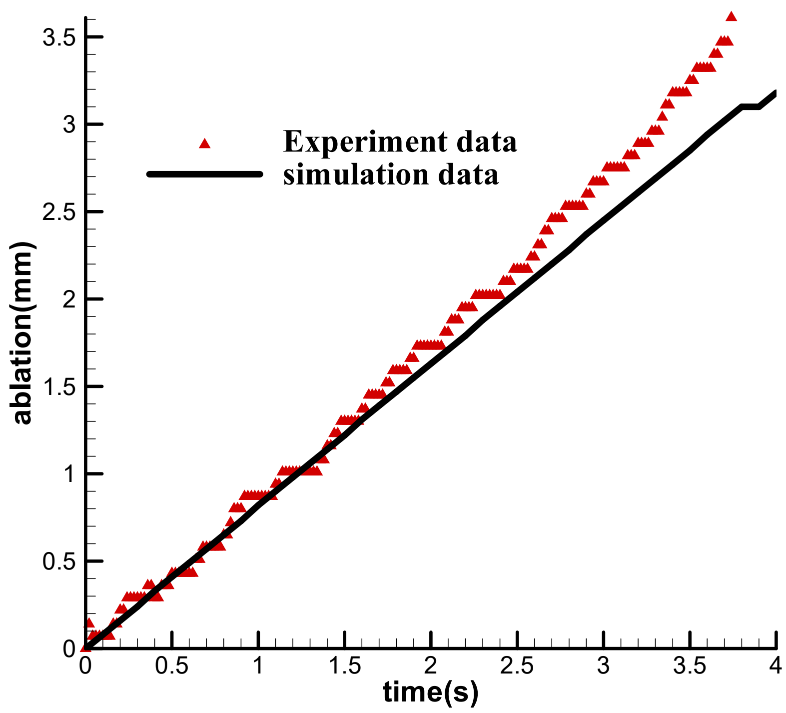


The temperature distribution

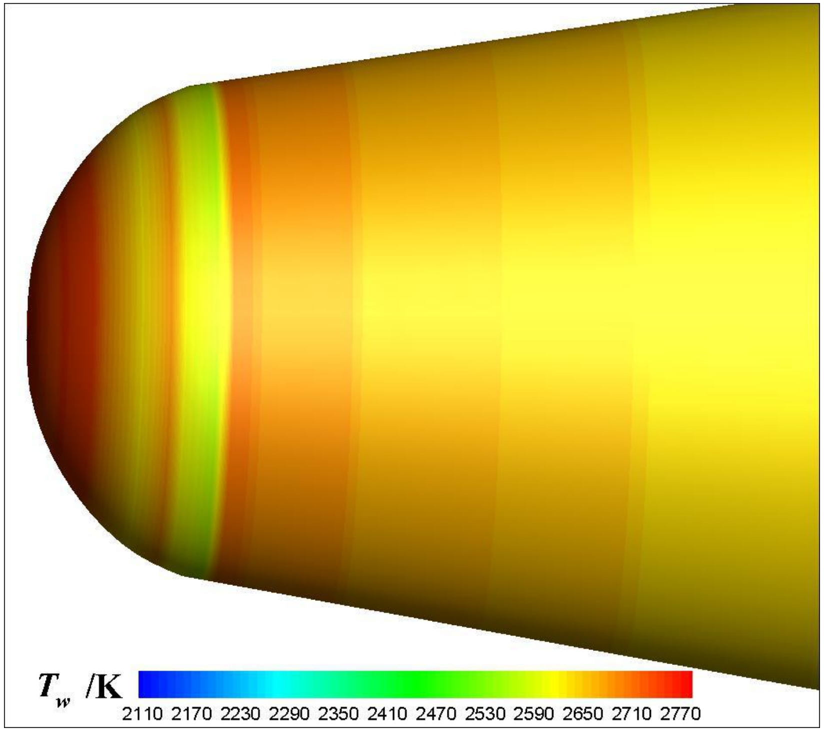


The wall friction distribution

The Ablation Results



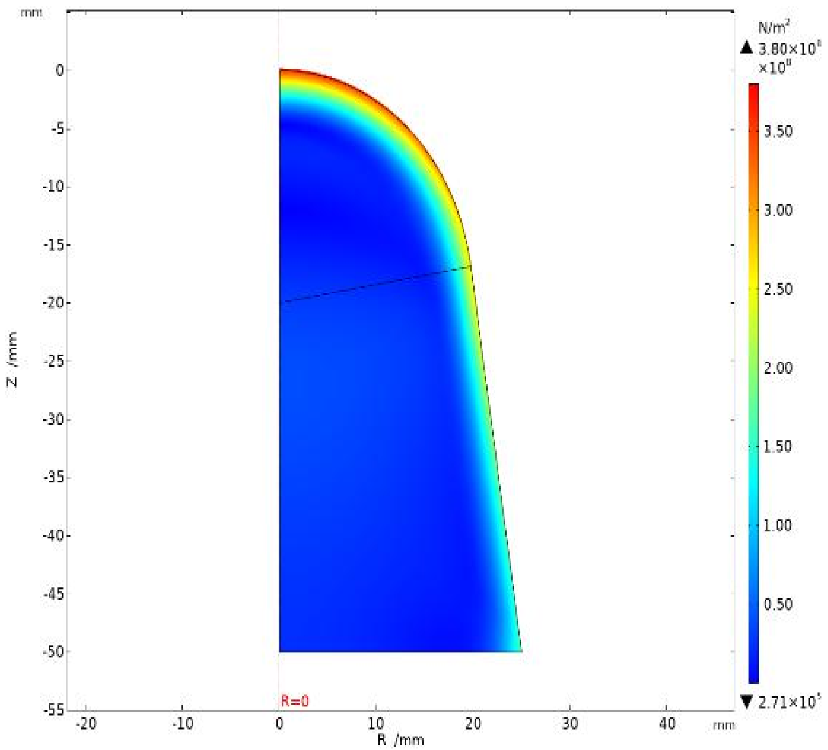
The ablation recession with time



The surface temperature distrubtion

The Thermal stress analysis

The posttest shape (Model #1)



The von mises stress distribution at 4th second (without ablation)

The brief concludsion:

1. The ablation recession rate and the final ablation shape is consistent with the experiment results.
2. Higher viscosity leads to the lower mass loss rate by the motion of melt layer, more energy are balanced by the evaporation. The surface temperature increases and the total mass loss rate decreases.
3. The thermal stress caused by the temperature gradient exceeds the material's strength, which cause it to fragment.

The future work:

1. Employing the Numerical method to simulate the motion of melt layer is necessary to handle the asymmetric factors.
2. The theory model is helpful for us to comprehend what happened during the ablation and fragment process, while it is limited for the meteorite with some random structures.
3. The mass loss of the melt layer is sensitive to the viscosity and thermal conductivity of the molten compound, which should be measured precisely.

Thanks for your attention

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