Micrometeoroid Entry as a Fluid-Structure Interaction Problem: A Coupled DSMC-FEM Approach

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Micrometeoroid Entry

It is estimated that one hundred thousand tons of meteoric material impact the Earth's atmosphere every year [1], with the bulk of these impactors being micrometeoroids, or meteoroids on the order of a gram, or smaller. Micrometeoroids are primarily studied using radar, where their properties are inferred from the signal-to-noise ratio of radar signals that are reflected off the surrounding plasma.

Motivating Problem

The entry of micrometeoroids into the atmosphere is a complex physical process, which includes ablation, rarefied hypersonic flow, and plasma formation. The models used to correlate radar data to micrometeoroid properties are based on simplifying assumptions (e.g. isothermality) which may not always be applicable [2]. There is no first principles model which simultaneously captures the coupled physics of micrometeoroid entry into the upper atmosphere.

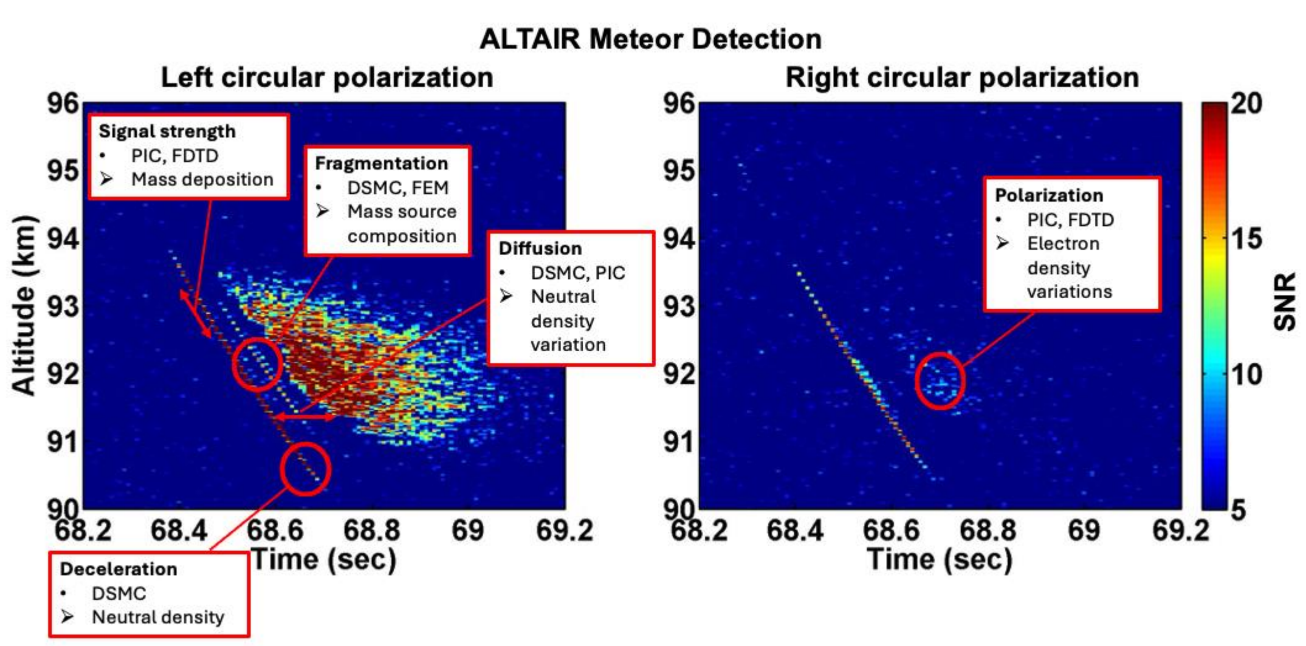

Figure 1: Representative RTI image of a meteor observed at ALTAIR, showing (left) left-circular polarization and (right) right-circular polarization with annotated phenomena and relevant simulation methodologies to extract measurements of atmospheric parameters.

Project Goal

This work demonstrates progress towards the development of a coupled solver that tackles micrometeoroid entry as a fluid-structure-thermal interaction problem. Within the fluid, the flow field is solved using the Direct Simulation Monte Carlo (DSMC) method. Within the micrometeoroid, the thermal and structural properties are solved using the Finite Element Method (FEM). We couple their solution through interfacial conditions at the micrometeoroid surface. This solver would enable the ability to investigate transient meteoric phenomena and improve our understanding of micrometeoroid radar measurements.

DSMC Method

The DSMC method [3] uses weighted macroparticles to approximate the solution to the Boltzmann equation, which describes the evolution of nonequilibrium flows. It accomplishes this via two steps: deterministic particle motion and stochastic particle collision. From these particles' motions and velocities, we can determine the spatiotemporal properties of the flow, including velocity, density, and pressure.

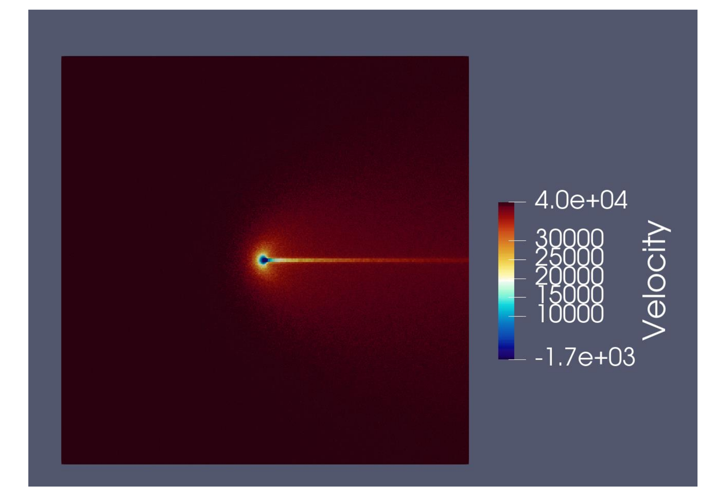

Figure 2: Meteoroid Flowfield

Finite Element Method (FEM)

The FEM is a numerical method for solving partial differential equations (PDEs). By spatially discretizing the domain into elements and applying a shape function approximation to the solution within each element, we obtain an ordinary differential equation (ODE), which we advance with a time integrator of our choice [4].

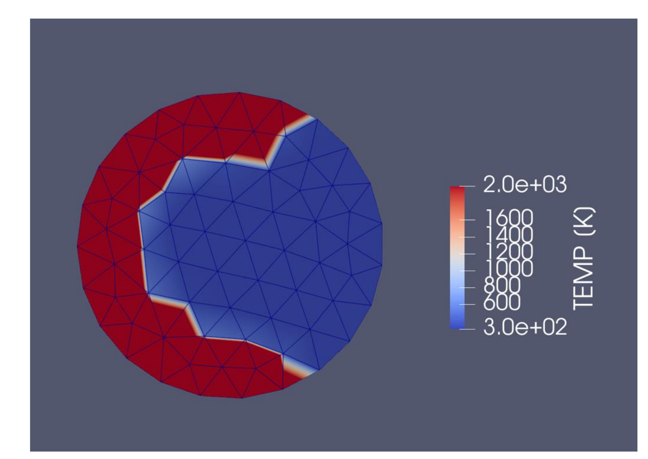

Figure 3: Meteoroid Temperature

DSMC-FEM Coupling Strategy

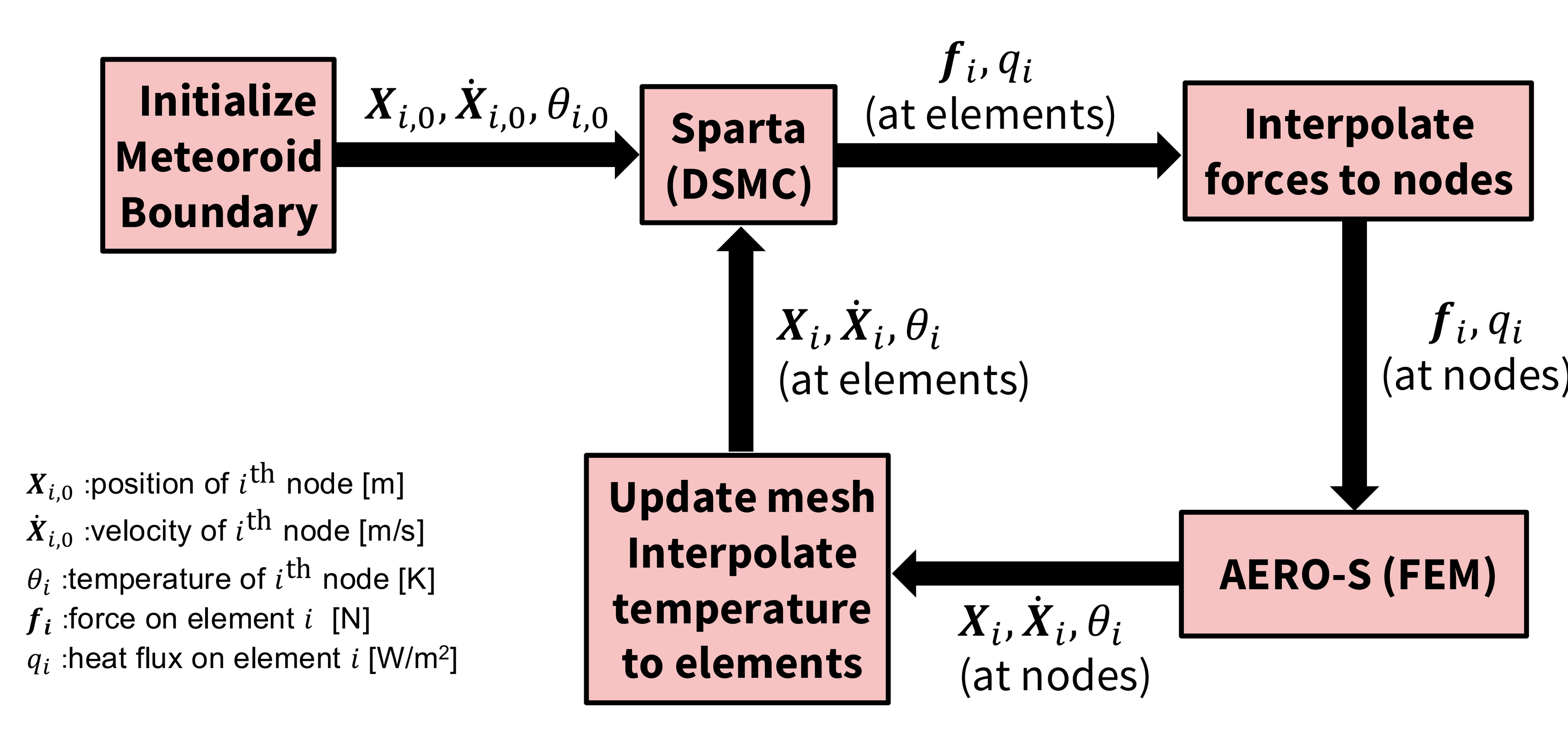

Figure 4: EMP generation during the simulation

Results

Particle Properties	
Particle Number Density	10^{20} particles / m^3
Particle Temperature	200 K
Inflow Velocity	40000 m / s
Composition	O, N
Boundary Properties (2 cm x 2 cm box)	
Left	Inlet - Freestream
Top/Bottom	Specular Reflection
Right	Outlet
Surface (radius = 0.01 m)	Diffuse Reflection (T_0 = 300K)

Table 1: Simulation Properties

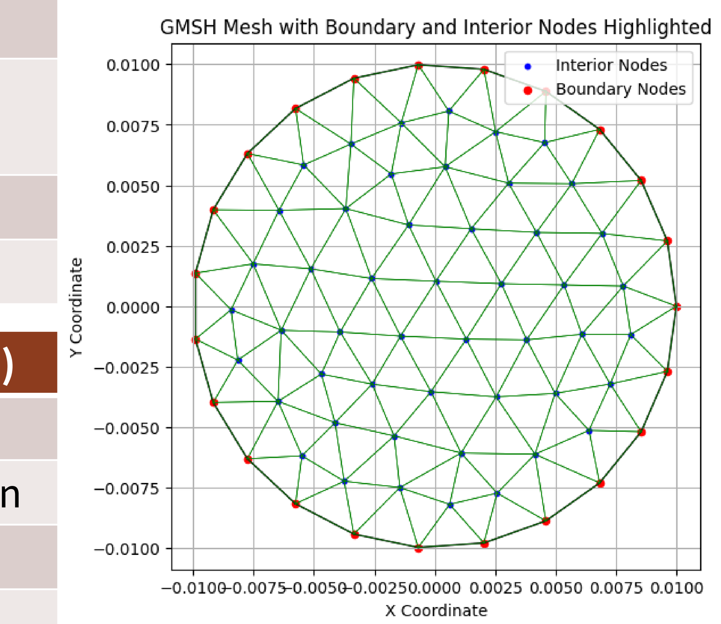

Figure 5: Meteoroid Discretization

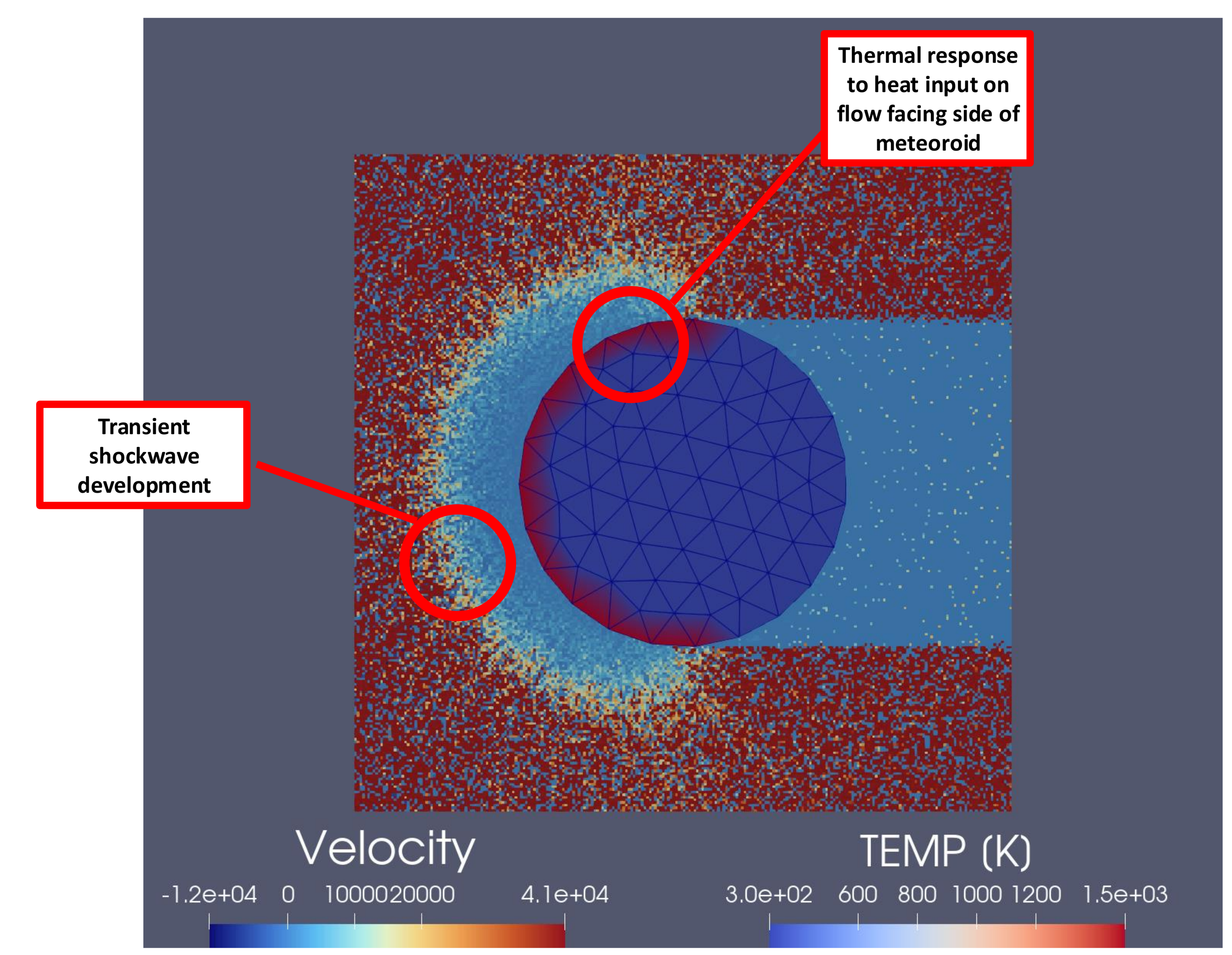

Figure 6: Coupled DSMC-FEM meteoroid flow solution, qualitative

Conclusion

This work demonstrates the successful configuration and integration of a DSMC code (SPARTA) and a FEM code (AERO-S) for rarefied fluid-structure-thermal interaction. Future work will include parallelized high-fidelity simulations using accurate material and atmospheric properties to reproduce transient meteoric phenomena.

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Further Information

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