Simulating Hypervelocity Particle Impact and Survival Probabilities in Aerogel

Gautam Wilkins[1] and Gerardo Dominguez[1] , [1]University of California, San Diego(gdominguez@ucsd.edu)

Introduction

The deceleration of a hypervelocity particle in aerogel generates a significant amount of heat, which can result in partial to total ablation of the particle. Understanding this process in detail is critical to the use of aerogel collectors as a scientific instrument for sample return missions (e.g. Stardust) [1]. While some theoretical modeling of the capture process has been done [2, 3], detailed physical models of thermal transport during the deceleration of hypervelocity particles in aerogel are not well developed. A general model of track formation caused by the impact of such particles has recently been developed [4], and here we demonstrate that such a model may be extended to predict the conditions experienced by the particle during the course of the collision.

Theoretical Model

The model consists of three components: a particle velocity model, an aerogel temperature model, and a conductive heat transfer model to determine heating of the particle. A detailed description of the particle velocity model and the aerogel temperature model that we use may be found in [4], although we will repeat the associated equations here for clarity.

The deceleration of a particle as it impacts aerogel may be written as:

$$\frac{dv}{dt} = -\frac{3}{4}\left[C_d\left(\frac{\rho_a}{\rho_g}\right)\left(\frac{v(t)^2}{r_g(t)}\right)\right]$$

where $\frac{dv}{dt}$ is the instantaneous acceleration of the particle, $v(t)$ is the velocity of the particle at time t, $r_g(t)$ is the radius of the particle at time t, ρ_a is the density of the aerogel, ρ_g is the density of the particle, and C_d is a dimensionless drag coefficient .

If we assume that the aerogel track walls and vapor are in thermal equilibrium, then the temperature of the aerogel track walls and vapor is:

$$T_v(t) = \frac{\left[f_Q(t)C_d v_g^2\left(\frac{r_g}{r_T(t)}\right) - H_v f_v(t)\right]}{\left[\overline{C_p} + \left(\frac{f_v}{\gamma-1}\right)\frac{1}{\overline{m_v}}k_b\right]}$$

where $f_Q(t)$ is the fraction of particle energy that is converted to heat, $r_T(t)$ is the radius of the track, H_v is the heat of vaporization of the aerogel, f_v is the fraction of aerogel in the track that is converted to vapor, C_p is the average heat capacity, and m_v is the average molecular mass of the aerogel material.

If we assume that the particle is in direct contact with the heated aerogel, then we may apply the heat conduction equation to determine the amount of thermal energy that is transferred from the aerogel to the particle. The three-dimensional heat equation in spherical coordinates is:

$$\frac{\partial T}{\partial t} = D\left[\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2\sin^2(\phi)}\frac{\partial^2 T}{\partial \theta^2} + \frac{\cos(\phi)}{r^2\sin(\phi)}\frac{\partial T}{\partial \phi} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2}\right]$$

Taking the particle to be an isotropic sphere and assuming that the temperature of the surrounding aerogel is uniform on the particle's surface, the equation above reduces to a one dimensional equation:

$$\frac{\partial T}{\partial t} = D\left[\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r}\right]$$

Solving the above equations simultaneously yields the velocity of the particle as a function of time, the temperature of the aerogel track walls and vapor as a function of time, and also the temperature of the particle, as a function of position and time. The only unknown parameters in the above equations are f_Q and f_v. If we assume that ablation occurs once the temperature of the particle surface exceeds a critical temperature (material dependent), our model allows us to calculate the expected ablation experienced by a particle during impact.

Results

The plots in this section were generated from a computational implementation of the theoretical model presented in the previous section. We express the survival fraction of a particle as the ratio of the final particle radius (after it has come to rest in the aerogel) with the initial particle radius. The survival fraction of the particle varies as a function of initial particle size, initial particle velocity, f_Q, and f_v.

As one might expect, higher initial velocities, and greater values of f_Q result in a lower survival fraction due to the increased heat generated by the deceleration process. Higher values of f_v, on the other hand, cause the survival fraction to increase. It takes a large amount of thermal energy to vaporize the aerogel, resulting in

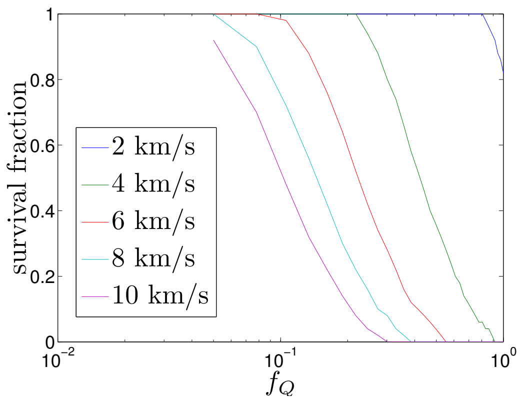

Figure 1:

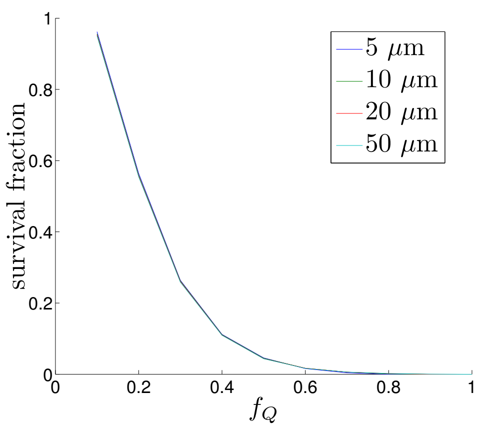

Figure 2:

lower aerogel temperatures as the fraction that is vaporized increases.

Figures 2 and 3 are plots of f_Q versus survival fraction for particles with different initial radii. There appears to be very little difference in the survival fraction of micron sized particles (Fig. 2) but when the particles become nanometer sized, the survival fractions begin to change based on the radius (Fig. 3).

Figure 1 is a plot of f_Q versus survival fraction for particles with different initial velocities. For the low velocity of 2 km/s, very little ablation occurs, even as f_Q approaches 1. At the high velocity of 10 km/s, ablation occured for all the values of f_Q that were tested. At that velocity, the particle was completely destroyed for all choices of f_Q above 0.3.

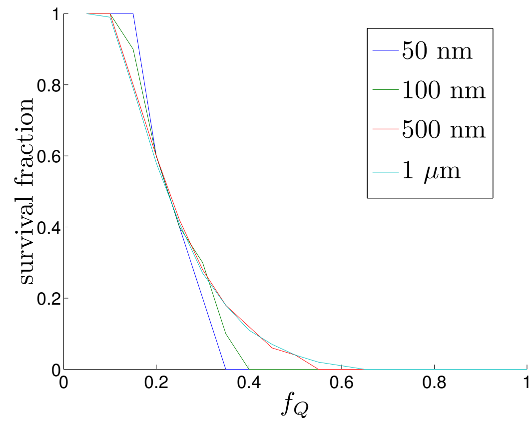

Figure 3:

Future Work

Currently, the model does not take into account the radiative transfer of energy between the particle and the surrounding aerogel, nor does it take into account possible radiative preheating of the aerogel before the particle comes into physical contact with it.

Future work will address these issues. A model of the bow shock formation will be introduced, and the heat conduction equation modified accordingly. Addressing the issue of radiative transfer involves adding a radiative model that, in conjunction with the conductive model, heats the particle and aerogel.

Finally, a detailed comparison between the model's predictions for the survival fraction and its dependence on f_Q and f_v will allow us to constrain these unknown parameters and the physical conditions experienced by captured projectiles with higher degrees of certainty.

References

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