The Use of In-Space Manufactured Solid Foams for Aerocapture

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Abstract

Aerocapture has been investigated as a means of capturing platforms into a planetary orbit using minimal mass [1]. Using aerocapture, the drag created by the spacecraft traversing a planetary atmosphere can provide sufficient deceleration to capture it into a bound orbit [2]. The delta-V delivered through aerocapture is a function of the drag force, the mass of the platform, the density profile of the atmosphere as well as the entry profile. This poster explores a novel method of increasing the drag force by using in-space manufactured solid foams to create a large diameter aeroshell. The density of the foam is critical, as it affects both the scale of the aeroshell and the aeroshell's mechanical and thermal properties. A sensitivity analysis was carried out to find a suitable foam density and aeroshell dimensioning that would be suitable for an aerocapture on Mars. The final aeroshell parameters where then used in a Direct Simulation Monte Carlo (DSMC) to more accurately evaluate the mechanical and thermal loads.

Context

For a given payload mass, there are two options for providing the delta-V required to capture the spacecraft in the planet's orbit 1) a trajectory with a pericentre in the denser lower atmosphere 2) a grazing trajectory in the upper atmosphere with a large aeroshell. In approach 1 the low minimum altitude results in a high maximum heat flux. In approach 2 the platform has a higher minimum altitude and so lower maximum heat flux. A lighter TPS is required for this approach [3] but the diameter of the vehicle needs to be much larger for the same effect.

In-space manufacturing technology opens the possibility of designing space products that are tailor made for their application, free from the constraints of ground-based manufacturing and launch. In the case of an aeroshell designed for aerocapture, in-space manufacturing could enable the construction of an aeroshell with a large diameter and low mass resulting in an ultra-low ballistic coefficient. This aeroshell would require a high specific strength to support the deceleration of the spacecraft. Solid foams have high specific strength and low density [4] so make an interesting candidate material for the aeroshell.

The foam aeroshell must be capable of surviving the aerocapture's atmospheric pass. To survive, the aeroshell must be capable of supporting a high mechanical load and a high heat flux while passing through the atmosphere. This is somewhat of a balance, as higher passes require larger deceleration to capture the spacecraft in the planet's orbit, whereas lower passes have higher heat flux. To examine the conditions for which a foam aeroshell would be suitable, a trajectory model was used to carry out a sensitivity study. Mechanical and thermal models were used to understand whether or not the aeroshell would survive.

Trajectory Model

The trajectory analysis was performed using a 3 degree-of-freedom simulation code developed by Bailet et al [5]. The Martian atmosphere parameters were derived from the results of the Mars Pathfinder mission [6].

A sensitivity analysis was performed assessing the effect of entry flight path angle and ballistic coefficient (ß). The baseline geometry of the aeroshell was fixed (see Fig. 2) with only one variable being the radius of the aeroshell (a). ß was calculated using equations 1 and 2.

$$\beta = \frac{m_{AS} + m_{PL}}{C_d \pi a^2} \quad (1)$$

$$m_{AS} = \rho_{Foam}\left(Vol_{Front} + \frac{1}{3}\pi(a^2 + ab + b^2)h\right) \quad (2)$$

Here m_{AS} is the mass of the aeroshell, m_{PL} is the mass of the payload, C_d is the drag coefficient, b is the radius of the central hub containing the payload, h is the thickness of the aeroshell, Vol_{Front} is the volume of the foam around the central hub, and ρ_{Foam} is the density of the foam. In addition, the spacecraft has an entry interface speed of 5.5 km/s and a fixed mass of 12.5 tonnes (10 tonnes payload). The target orbit aims for a range of apoapsis altitude between 30,000 and 40,000 km.

Mechanical and Thermal Models

The dynamic pressure on the skirt section of the aeroshell is one of the critical parameters to design the mission. Using the Gibson-Ashby model [4], the mechanical properties of various densities of PEEK-based foam were assessed. The aeroshell was modelled as an annulus plate, fully supported by the payload central hub using plate theory [7].

The mechanical Factor of Safety (FoS) is derived from this analysis and displayed along side the maximal heat flux at the nose in Fig. 1 and represents the maximum stress found by the mechanical model as a proportion of the tensile yield strength of the foam.

Alongside the FoS, Fig. 1 display the peak heat flux at the nose of the aeroshell for the different ballistic coefficients. For this purpose, the Sutton-Graves approximation for Mars was used [8], this will help us determine in future analysis if the nose heatshield could be constituted of disposable PEEK-based foam or if a traditional TPS needs to be used at the nose.

Finally, dsmcFoam+ [9], a direct simulation Monte Carlo (DSMC) solver was used to more accurately evaluate the mechanical and thermal loads allowing us to confirm our initial dimensioning. The simulation was performed for a velocity of 5.16 km/s, an altitude of 91 km and the geometry shown in Fig. 2.

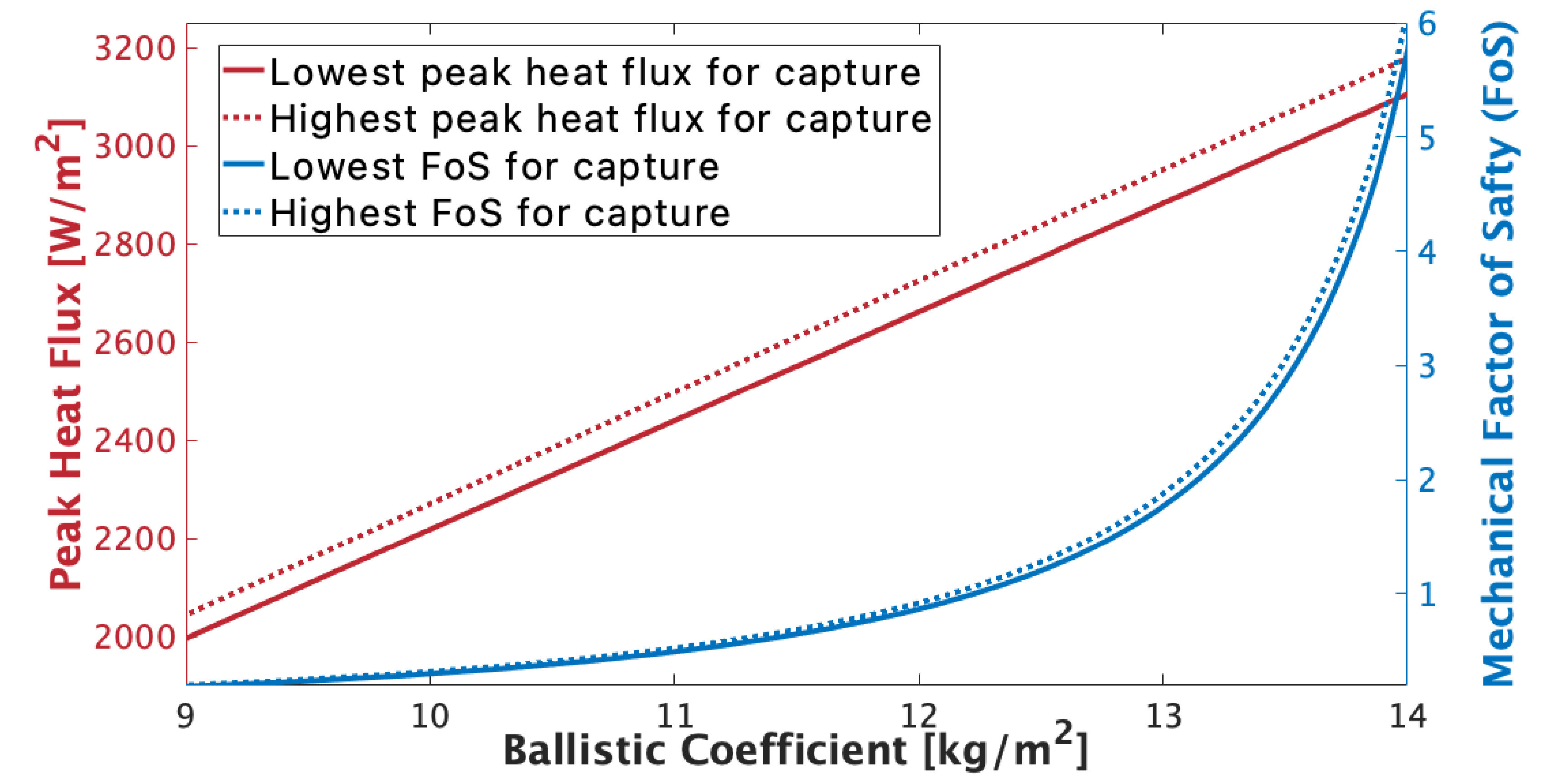

Figure 1: Peak heat flux and mechanical FoS for captured trajectories as a function of ß

Performances

The final aeroshell design was selected based on the mechanical performance. The final design has a foam density of 86 kg/m^3, a ß of 12 kg/m^2 and an outside diameter of 25.5 m (a=12.75 m). The performance of this aeroshell has been compared with a chemical propulsion system and the inflatable entry system HIAD [3] system in table 1. The analysis shows that the aerocapture with a foam aeroshell is able to save half of the allocated mass and three quarters of the volume for the same mission compared to the chemical propulsion solution. In comparison with a HIAD type system, the foam aeroshell is not able to perform a full entry but could be a enhancement to HIAD or an intermediate stage allowing a first aerocapture with the foam aeroshell from a more constraining interplanetary approach before the final entry with HIAD.

Table 1: Foam aeroshell performance compared to HIAD and chemical propulsion

System	Foam Aeroshell	HIAD (Ø23m)	Chemical Propulsion
Mission Context	12.5 tonne mission Aeroshell Ø25.5 m	109 tonne mission Aeroshell Ø23 m	12.5 tonne mission Engine I_{sp} 370s
Percentage of Mission's Mass	20%	25%	40%
Storage Volume	3 m^3	120 m^3	11 m^3
Ballistic Coefficient (ß)	12 kg/m^2	135 kg/m^2	N/A
Heritage	None	Demonstrator tested [10]	Extensive heritage

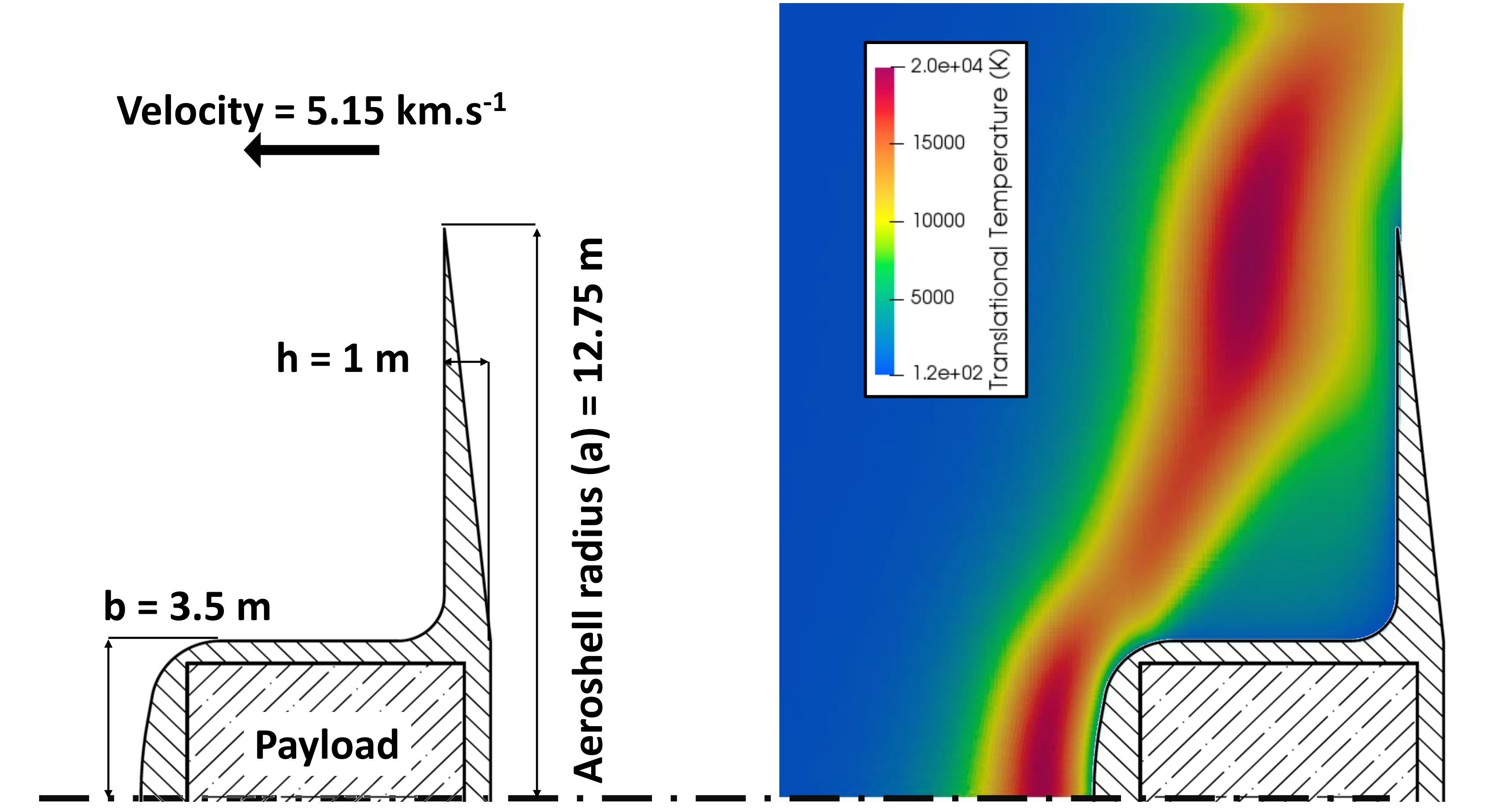

Figure 2: Cross section of the axisymmetric aeroshell (left) and DSMC results for the maximal heat flux point of the selected trajectory (right)

Conclusion

The in-space manufactured foam aeroshell presented in this poster shows promises to deliver a 12.5 tonne mission (10 tonnes payload) in Martian orbit using an aerocapture manoeuvre (minimum altitude of 91 km).

Further studies will allow the validation of thermal and mechanical properties of the proposed PEEK-based foam and demonstrate in-orbit manufacturing of such large scale systems. This novel approach could allow a drastic change in the future mission concept where qualification and repair of the system in-flight becomes a reality thus increasing system reliability.

Acknowledgments

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