Dynamics of the movement of the descent vehicle in the atmosphere of Mars with the use of inflatable brakes in the lower atmosphere

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Abstract. Currently, more and more spacecrafts are being designed, to explore the planets of the solar system. One of the very important stages in the execution of such missions is the movement from the moment of deorbiting until the moment of approaching the surface. The entire descent trajectory from the moment of separation to contact with the surface is a very important stage and a very important object of research particularly in the field of Computational Fluid Dynamics (CFD). It is to this process that a series of articles by the authors is devoted. This article is devoted to the movement of the descent vehicle in the lower atmosphere. Some parameters of the descent vehicle movement at this stage of movement are analyzed. The importance of such research and the possibility of using inflatable braking devices are shown.

1. Introduction

This paper is the second part of a series of two papers dealing with the MetNet lander vehicle during the entry into the atmosphere of Mars. In this paper, we will focus on the descent of the lander vehicle in the middle and low atmosphere of Mars while the first paper deals with the entry in the high atmosphere. The MetNet mission aim at landing a set of Mars Meteorological Lander (MML) to study the climate and the physics of the atmosphere of Mars [1]. In the previous missions where a probe was landed on mars, the classic way to brake speed was to use parachutes and a solid heat shield with the use of retro propulsion at the final landing stage. This technique has proved that it can be used to land a probe on Mars with success. However, some other techniques are under development and one of them is the use of an Inflatable Braking Device (IBD) to brake the velocity and to protect the probe of high temperature conditions during the entry playing the role of a Thermal Protection System (TPS). The good point of this technique is that it enables to increase the mass of the payload thanks to the economy of a solid heat shield or fuel for the retro propulsion. Indeed, an inflatable braking system offers a high surface to decrease the velocity with the drag force but is very lightweight and compact when it is not deployed.
There are four stages during the descent of the lander vehicle for the MetNet mission. During these stages, two braking devices are used: the Main Inflatable Braking Unit (MIBU) and the Additional Inflatable Braking Unit (AIBU). The first one is used to brake the speed and as a heat shield in the upper atmosphere while the second one is used to decrease the velocity by mean in the middle and low atmosphere of Mars (figure 1 [2].)

![Figure 1. Landing process of the MetNet Lander Vehicle and geometry of the MIBU](image)

The concept of IBD can also be used for the reentry into the atmosphere of the earth. The Re-entry Inflatable Technology Development (RITD) is carrying out in order to use a system close to the MetNet one to ensure the landing on earth [3]. More information about the general use of inflatable devices and real tests carried out in the past can be found in the introduction of the first article of this series. For a more complete report, we can refer to [4] and [5].

In the previous article of this study, we have focused on stage I and stage II in the high atmosphere. In this paper, we will focus on the descent in the middle and low atmosphere. The aim of the whole study is to analyse the local repartition of aerodynamical stresses and the global value of lift and drag but also the temperature field in the close environment of the probe during the descent from the high atmosphere to the ground. We will also see the influence of various temperature boundary conditions for the wall of the descent vehicle which is an unknown parameter a priori.

2. Theoretical background, modeling hypothesis and preprocessing

Figure 2 sums up the study case (case 3) chosen in this paper. Cases 1 and 2 were studied in the first paper. The simulations were made with OpenFoam which is an efficient software for Computational Fluid Dynamic (CFD).

We found the values of temperature and pressure thanks to the Mars climate database [6] and we have chosen the same values of velocity and altitude as in [7] for this stage of the movement.

![Case 3: beginning of stage III](image)

As we can see in figure 2, case 3 is supersonic so that the flow is highly compressible. So for this case, we have used the solver rhoPimpleFoam which is adapted to transient compressible flows, so adapted to our study case. If we compute the Reynolds number, we find \( R_e \sim 3 \times 10^5 \) so the flow is turbulent. In the numerical resolution, we have chosen the k-epsilon model with a turbulent intensity of 1% and a characteristic length of the turbulent structure of 10 cm (an experimental study would be needed to precisely determine these values in such conditions). Because the turbulence is establishing in 3D, we have chosen a fluid domain with a small thickness equals to the length of the turbulent...
structures. During the simulation, dynamic viscosity is computed with a Sutherland law considering that the Martian atmosphere is fully composed of CO2 and for the heat capacity, we used the Janaf expression where the unknown parameters for both formulas can be easily found for CO2 in the literature. By the way, we need to specify a boundary condition for the temperature of the wall of the descent vehicle before launching the simulation. Because this parameter is unknown, we will try two temperatures of the wall (500K and 1000K) corresponding to close values that are encountered into the shock layer as we will see. So somehow, we have proceeded on an iterative way, waiting the first results for the temperature into the shock layer to choose the temperature of the wall in the next simulations. Here were the main modeling hypothesis for the preprocessing stage of our simulations. Let’s now see the results.

3. Results and analysis

In this case, the velocity reached a supersonic value of 700 m/s and the MIBU has been dropped. Figure 3 and figure 4 represent the temperature field and the pressure field around the lander vehicle for two temperatures of the wall (500 K and 1000 K). We observe different characteristics phenomena of the supersonic velocity. First of all, an attached shock wave is created on the tip at the bottom of the lander vehicle. This attached shock consists to a region where the temperature is increasing because of compression of the flow. There is also a bow shock all around the lander vehicle created by the blunt form of the upper part of the AIBU. Here again, the temperature increases with compression of the flow passing through this bow shock. We also see recompression of the flow above the lander vehicle in the wake. We can also well see the interaction between the attached shock and the bow shock near the tip which raise the pressure of the flow.

Figure 3. Temperature field at t=0.015s (simulated time) for an angle of attack of 0°.

Figure 4. Pressure field at t=0.015s (simulated time) for an angle of attack of 0°.

Figure 5 shows the repartition of pressure stresses around the lander vehicle at t=0.015s when the mean flow is steady enough. There are two components in pressure stresses defined as follow:

\[ T_{px} = -(p, \vec{n}) \cdot \hat{x} \]  

\[ T_{py} = -(p, \vec{n}) \cdot \hat{y} \]

Where p is the pressure, \( \vec{n} \) is the normal to the surface pointing the fluid, \( \hat{x} \) is the axis which direction is orthogonal to the velocity and \( \hat{y} \) is the axis of the velocity direction.
Figure 5. Pressure stresses on the lander vehicle at t=0.015s (simulated time) for an angle of attack of 0° (left: \(T_{px}\), right: \(T_{py}\)).

Left side and right side are defined in Figure 6. In Figure 5 left, the first rise of \(T_{px}\) is due to the detached shock. Then comes the effect of the bow shock on the bottom part of the AIBU. On the upper part, \(T_{px}\) becomes nil because pressure is low. The same kind of observations can be done for \(T_{py}\) (Figure 5 right) except that between 0.3m and 0.9m, \(T_{py} = 0 N/m\) because of the vertical side of the lander vehicle: the normal is fully along x axis. This visualization of pressure stresses around the descent vehicle following its contour is important because we have to keep in mind that the inflatable part is not a rigid body and the flow creates constrains which can lead to deformations that can be predicted knowing the local pressure stresses. Such a study of the deformation of the AIBU will not be carried out in this paper.

Another point is that by integrating these pressure stresses (which is equivalent to take the sum of the algebraic areas under left side and right side on figure 5, we find lift per meter \(L\) and drag per meter \(D\) (we express them in Newton per meter which is equivalent to divide forces per the thickness of the fluid domain):

\[
L = \int T_{px} \, dl
\]

\[
D = \int T_{py} \, dl
\]

Here, we constate the almost perfect symmetry between left side and right side and the fact that algebraic areas compensate for \(T_{px}\), giving a lift close to 0 N and that they add together for \(T_{py}\) giving high values for drag. \(L\) and \(D\) can be found on Table 1 for this case. The influence of the temperature of the wall seems to change a little the values of lift and drag per meter but there is the same order of values even if we double the temperature of the wall. Because we are in a 0° angle of attack configuration, we can find the global lift and drag by integrating the value of lift and drag per meter doing a revolution around the axial axis of the descent vehicle.

These results were found assuming that we can neglect viscous contribution that is to say pressure contribution is higher than viscous contribution in lift and drag values. This hypothesis is checked when the forces are steady enough as we can see in Figure 7.
Figure 6. Definition of left side and right side with the orientation of the contour (origin: (0,2)) each point is a point where data are evaluated.

Table 1. Values of lift and drag per meter for various temperatures and for an angle of attack of 0° at t=0.015s.

| $T_{wall}$ | Lift per meters $L$ | Drag per meters $D$ |
|------------|---------------------|---------------------|
| 500 K      | 5.69 N/m            | 1980.3 N/m          |
| 1000 K     | 4.18 N/m            | 1909.5 N/m          |

Figure 7. Pressure and viscous forces per meter function of time for an angle of attack of 0° (left: lift per meter, right: drag per meter).

4. Conclusion
As a result of the work performed, which this article is devoted to, the following conclusions can be made:
1. This stage of movement, in the lower layers of the atmosphere is a very important stage, since the speed value is still quite large so that we have to be sure the drag force will slow down the probe from this speed value to a reasonably low speed near the ground.

2. The temperature into the shock layer in the close environment of the probe for these speed values and for the chosen hypothesis of modelisation was found to be about 500 K. So this study provided results to ensure a design of the MetNet probe which will guarantee the integrity of the descent vehicle.

3. Some others studies would be needed to help to determine some unknown data for example the intensity of the turbulence and the size of turbulent structures in such conditions which determine the structure of the flow in the simulation. And from a numerical point of view we have to be sure that the k-epsilon model chosen in this study ensure a good modelisation of the turbulence.

4. By the way, the fundamental possibility of using inflatable braking devices for landing in a priori difficult conditions of the planet's external environment is shown.

5. It is necessary to carefully study all stages of the descent vehicle's motion both from a numerical and an experimental point of view when designing future missions to explore the planets of the Solar System.

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