OVERVIEW OF DUST EFFECTS DURING MARS ATMOSPHERIC ENTRIES : MODELS, FACILITIES AND DESIGN TOOLS

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ABSTRACT

Mars atmosphere periodically witnesses dust storm that may leave solid particles in suspension for a long time. According to their high velocities, when reentry vehicles encounter such dust clouds, even small particles can induce significant damage to the TPS, due to the high kinetic energies involved. Charred layer erosion is the most evident effect of dust clouds encounter, but other less awaited effects are present that need modelling for a comprehensive assessment of dusty flows.

This paper proposes an overview of these effects within the frame of Mars entries. This review encompasses modelling and ground testing, with emphasis on limitations and unresolved problems, aiming at highlighting desirable progress in the field.

1. INTRODUCTION

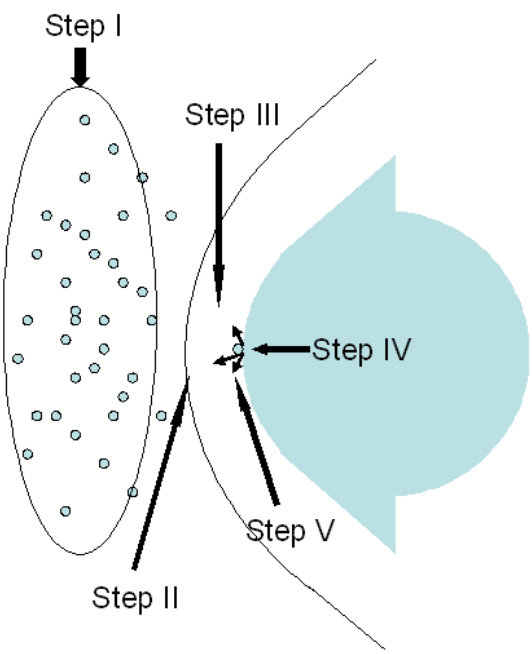

Fig.1.: Main events related to particles laden flows

Addressing vehicle response to dust clouds encounter during hypersonic reentry supposes to master different physical phenomena and acquire various parameters. The first part of the paper will be a review of all evidenced phenomena which make the dusty flows so unique compared to "usual" clear flows, and a "state of the art" of physical models. Then we will address the ground tests facilities and the simulation tools that we have at hand to make the assessment of planetary probes, especially the TPS subsystem. We will conclude with a discussion on validity and limitations of models, experimental and numerical tools, in order to highlight the directions towards further improvements.

2. PARTICLES DESCRIPTION (step I)

This includes all the data required to be able to address next steps resolution.

First and most important parameter is the particles concentration (usually defined in g/m3). Second most important parameter is the particles velocity. In our reentry problem, this parameter is defined by the vehicle velocity which is several orders of magnitude higher than any free flow deviation from rest (wind…). Third and fourth parameters to know are the particles density and size (or size distribution). These factors will greatly affect the particles slow down described in chapter 4. They also influence the particles temperature evolution, as well as the potential radiative heating (emitted by the hot particles) induced.

Since the first measures of Viking probes, knowledge of Mars atmosphere particles has continuously improved, and is still improving. Our present baseline description is based on EMCD Martian climate global modelling [1]. This database, and most other, make the assumption of a direct correlation between dust content and visible light optical transmission, modelling it as in Eq.1.

$$M = \tau / DR \qquad (1)$$

where M is the total amount of dust in the atmosphere column above ground, τ the optical depth (a value of 1 means a severe environment, 5 is among the higher values during global dust storms), and DR is a scaling parameter (m^2/kg).

Values of DR depends on dust scenarios, and may vary between such values as 200 and 500.

Of importance is the dust content vs altitude, as dust is more threatening as altitude is higher, due to the high velocities of entry trajectories at upper altitudes.

Whereas in Earth entries water clouds top is generally less than 15km, on Mars, models predict dust as high as 70km (see Fig.2).

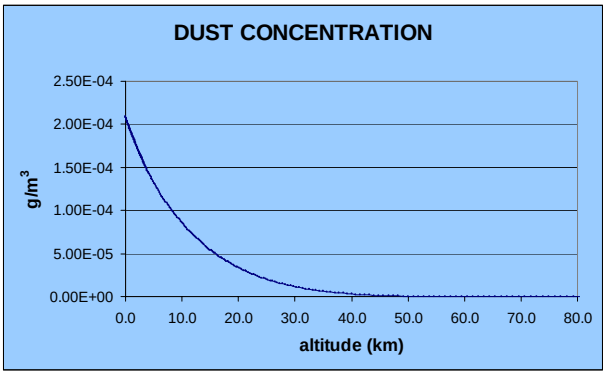

Fig. 2 : Dust concentration vs altitude @ τ=5

By chance, the dust content is also low, such that though velocities are important, erosion remains tractable.

Interesting also, when it comes to ground testing, are the characteristic values of dust flow that have to be reproduced to be representative. On Fig. 3 and Fig. 4 such data are depicted for a typical Mars entry (V≈ 5000 m/s, FPA ≈ 15°). It may be observed that even in the hypothesis of full particles energy transmission to the probe, this additional energy (about a few tenth of kW/m^2) remains small compared to usual convective heat fluxes (several hundreds of kW/m^2).

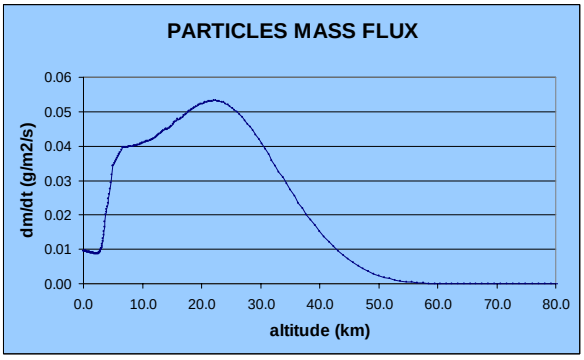

Fig. 3 : Dust mass flux vs altitude – τ=5

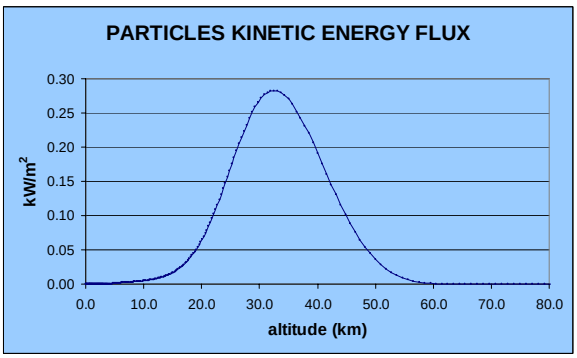

Fig. 4 : Dust kinetic energy flux vs altitude – τ=5

This last curve is particularly of interest as the erosion rate is roughly proportional to these values. As the velocities in ground facilities are much lower than in flight, the more simple way to reach comparable environment is to increase the dust concentration. Two means are possible thus for : keep particle diameter and increase number per volume, or keep number per volume and increase diameter.

For instance, as ground facilities velocities are about 1/10 of actual velocities, this would mean increase particles diameter by a factor of the same order of magnitude

$$\left(\frac{R^3_{ground}}{R^3_{flight}} = \frac{V^3_{flight}}{V^3_{ground}} \text{ i.e. . } R_{ground} = 10R_{flight}\right)$$

3. SHOCK/PARTICLES INTERACTIONS (step II)

This very brief event may be of importance in the next steps of particles/flow interactions. If the shock is strong enough, and if the particles have low mechanical characteristics (water drops, brittle material), this shock crossing can induce particles break-up. The smaller particles created during break-up can be more slowed down during the subsequent shock layer crossing than the initial larger particles which gave them birth.

Preceding phenomenon concerns shock influence on particles. Inversely, particles can "shatter" the shock and induce flow perturbations whose consequences are not well known (and we found very little literature on this topic). But these perturbations may be suspected as one of the potential origins of observed heat fluxes augmentations that are discussed in chapter 5.

The particles can even disappear, due to phase changes. Break-up can thus also lower the particles mass rates which impact the wall.

4. SHOCK LAYER CROSSING (step III)

This is one of the most critical steps in particle laden hypersonic flows. According to shock level, flow density and flow temperature, particles are slowed down, deviated and heated.

With the very blunt shapes of Mars Entry Capsules, deviation will only be important for the smallest particles (in a study on CNES MSRO orbiter of the Mars Premier program, we could observe that particles over 1µm where almost unaffected and made a bee line to the TPS [2]).

The slow down is on the contrary important for a much wider range of particles dimensions, and a good knowledge of this phenomenon is very important for the subsequent response of the TPS against particles impact (which at first order depends on the particles kinetic energy).

On the other side, the particles dissipate energy and momentum in the surrounding flow, which can have an influence on the overall flow behaviour, down to the boundary layer over the TPS.
Particles heating is one more phenomenon to account for as the seeded shock layer can subsequently radiate to the TPS more than the usual clear flow (particles are small and are very quickly in equilibrium with the surrounding flow, reaching temperatures of some thousands Kelvin). Moreover, if particles are sufficiently heated, they can vaporize or sublimate at least partly, thus reducing TPS wall erosion.
The last effect to be listed is the consequence of the particles on the gas mixture behaviour as compared to clear flows. All situations encountered thus far involved too small concentrations (less than 1 g/m3) to have a significant effect, and the hydrodynamics and particles histories could be treated uncoupled. This assumption must however be verified before any dusty flow assessment.

5. PARTICLES/TPS INTERACTION (step IV)

This is the most visible consequence of dust presence on the vehicle entry. With the high velocities considered, the particles can erode ten times and much over their own mass which can give significant TPS recession. The vehicle design must take this effect into account, with sufficient margins to prevent vehicle demise, but not so much as to preclude interesting payload/EDLS ratio.
More indirect effect is the roughening of the wall. If this roughening is sufficiently important, premature transition can occur in the boundary layer thus increasing the heat load to withstand.
Heat load augmentation has been observed many times in ground tests on dusty flows, but is believed not to be only attributed to transition triggering. Other effects are suspected which induce heat fluxes augmentation as high as 2 times the clear air heat fluxes (and supposedly over). These fluxes augmentation are the second known effect in importance (after mechanical erosion) that dusty flows induce over reentry vehicles.

5.1. TPS erosion

A classical modelling used to predict the behaviour of eroded materials when impacted by particle is of the following type:

$$G = \frac{m_e}{m_i} = a \quad \rho^b \quad V^c \quad T_{wall}^d \quad D_p^e \quad \sin^f(\theta)$$

where G characterizes the ratio between the mass removed from the material during the impact and the impacting mass of the particle, ρ is the particles density (kg/m3), V is the particles velocity (m/s), T_{wall} the wall temperature (K), Dp the particles diameter (m), θ the incidence angle (degrees), (a, b, c, d, e, f) are parameters linked to each material.

In order to be able to evaluate the "G-law" for a given material, some experimental studies can be performed. They are four-fold:

- wind tunnel tests can be conducted, where particles are injected in the free stream [3] [4]. These experiments permit to observe the erosion created by multiple impacts on a given sample. The effect of the shape of the target and of the particles concentration can be observed ;
- single impacts can be studied using microguns particles at very high velocities [5] [6]. In that case, the damage due to former impacts, the influence of the sample shape and the effect of the particles concentration can not be evaluated ;
- samples can be launched at high velocities and cross clouds of particles placed on their path [7] influence of the sample shape and of the particles concentration can be evaluated, but the duration of the observation is usually shorter than in wind tunnel facilities;
- high velocity impacts can also be simulated using laser [8] [9] : for a given laser, it is possible to determine the size and the velocity of a particle which would provide the same pressure applied to the same surface area as the laser. This kind of experiment has the same drawbacks as the microgun, but adds to these ones the difficulty to validate the equivalence law.

5.2. Augmented heat fluxes

Through the modification of the flow field, particles also lead to the augmentation of the wall heat fluxes, and the direct consequences are a higher recession rate and/or ablation. This phenomenon can thus be threatening for a reentry vehicle.
Therefore, various studies found in the literature are dedicated to the evaluation of the heat fluxes modification by particles.
Some wind tunnel tests were performed in the 70's in the US, in order to evaluate the heat fluxes augmentations due to particles [10] [11]. Those tests were related to supersonic flows (Mach close to 6.1) laden with 100 µm SiC solid particles. The measurements obtained showed a significant increase of the heat fluxes when particles were injected (multiplication of the stagnation point heat flux by approximately 2).
However, the tests were not fully documented, and some valuable information such as particles velocity, roughness modifications of the sample were lacking. Similar tests were performed in Russia and published in the 90's [12], this time with 20 to 250 µm diameter particles of Al2O3 in a 2.4 to 4.2 Mach number flow. The stagnation point heat fluxes were multiplied by 2 to 6, depending on the test

conditions, but the results were also not fully documented.

Various assumptions could explain these augmentations of the heat flux at the stagnation point: shock intermittencies were observed during some shots, the roughness of the wall can be modified due to particles impacts on the wall and induce a heat flux increase, turbulence can be created by the particles wakes as proposed by Hove & Shih's [13] and partly confirmed by Direct Numerical Simulations [14]. Those could be observed at the same time.

We specially rely on Hove & Shih's model, as it proved consistent with careful wind tunnel tests that we performed during the 80's, showing that a dust/clear heat fluxes ratio of 2, comparable to laminar/turbulent ratio, seemed to be a realistic value. However, the large discrepancies between references may be a hint that the full understanding of the problem still remains to be uncovered.

6. DEBRIS (step V)

After impact, many debris are ejected back in the flow, including particle and wall material debris. The subsequent history of these debris is interesting to assess, as they can seed the boundary layer and modify its behaviour. Some secondary impacts are not to disregard, but the velocities involved are in principle much lower and should induce much less erosion than incident particles themselves.

One other less discussed effect is the debris shielding [15]. When they impact the wall, particles throw wall debris in the flow. If the incoming mass flux is very important, ejected debris can shield the TPS thus reducing the overall recession compared to a "nominal" situation. This effect is generally difficult to account for in design. However, we can face it in ground experiments if, for instance, we increase dust concentration to compensate for small velocities in order to get observable erosion.

An other side effect that has to be accounted for is the possible seeding rear flow by particles or debris that may have consequences wrt the planetary protection. This problem can be encountered for example in aerocapture sequences, when the payload is not fully protected by a back-cover and hosts a return vehicle that shall be proved safe from any living alien bio contaminant.

7. GROUND TESTS : MATERIAL EROSION

In next two paragraphs, we will stress on the ground tests that can give access to the most troublesome effects of dust or particles presence, namely the increased mechanical erosion, and the augmented heat fluxes. This first paragraph is devoted to material characterization vs particles impacts.

One popular device we use is the R2Ch facility situated at ONERA. This hypersonic wind tunnel is mostly dedicated to aerodynamic and fluid mechanics studies in clear air. At the end of the 90's, CEA engaged a modification with the help of ONERA staff to upgrade the facility in order to assess flow modifications by particles seeding (and especially heat fluxes augmentation). We use it now on a more regular basis to make the characterization of material response to dust impacts, since the velocities achievable in this tunnel (800 m/s) are interesting to assess material resistance to erosion.

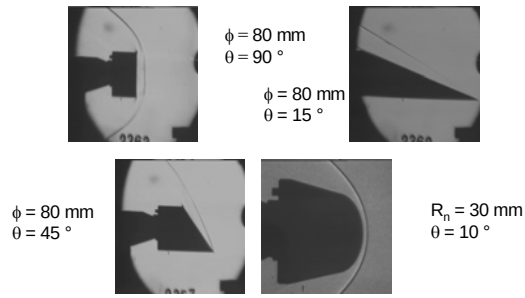

Fig. 6 : Type of samples used during R2Ch campaigns

One important limitation is that only cold material can be tested. Data coming from this source must so be extrapolated to high temperatures by the mean of careful high speed hydrodynamic computations. One other limitation is the rather low velocity of particles.

To overcome these two limitations, we rely on a small light gas gun CEA owns on its Bordeaux facility (MICA). This device was developed for the testing of materials impacted by particles at representative velocities (up to 5000m/s). It can work on cold material (either virgin or charred) and will be upgraded soon to account for hot material (material temperatures up to few thousands Kelvin are targeted).

Its main advantages are the particle velocities which should be closer to actual particles velocities encountered in Martian re-entries, and its capacity to launch small particles (200µm up to now, investigations are underway to launch smaller particles), which very few light gas guns are able to perform.

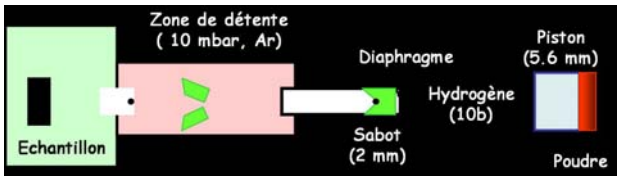

Fig. 7 : sketch of MICA facility

Its main drawback is that it cannot throw multiple particles simultaneously, and the cumulative effect of

successive impacts, which is more likely to increase the material erosion vs isolated impacts, cannot be simulated yet. This effect must thus be extrapolated through high speed hydrodynamic computations, as for the R2CH tunnel presented before

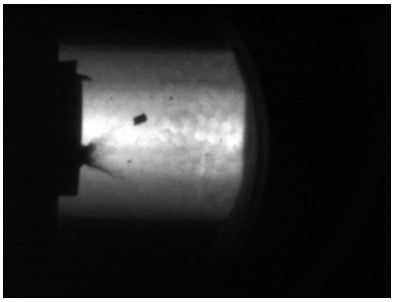

Fig. 8 : view of ejecta during one shot @ 4000m/s

8. COUPLED ABLATION/EROSION

Preceding devices address only the TPS mechanical response. As dust encounter occur at a time when the TPS is heating, charring and may be ablating, we can either suppose that erosion and ablation problems are uncoupled and treat it separately, or look for a mean to apply simultaneously erosion and heat fluxes to the material. This is done in few facilities. Two of them are our most preferred candidates, as they can give access to “true” Martian atmosphere simulation : VKI’s minitorch, and EADS/ST’s SIMOUN.

8.1. VKI minitorch

The VKI Minitorch Facility is a relatively small scale inductively coupled plasma (ICP) torch with a maximum anode power capability of 15 kW. It was designed as a test bed facility preceding the large 1.2 MW VKI Plasmatron. Typical gas flow rates are of the order of 1 g/s, with a radio frequency (R.F.: typically 27.12 MHz) vacuum triode oscillator operating at up to 6kV.

This facility is ideal for testing and implementation of experimental configurations and diagnostic tools.

Plasma discharge, in the minitorch, takes place in a vertically mounted quartz tube with an inner diameter of 3 cm. The gas injection system consists of a ring of injection ports at the base of the cylindrical inner block supported inside this quartz tube.

The quartz tube exhausts into a vertical cylindrical test chamber with a height of 120 cm and radius of 30 cm. This exhausted gas forms the "plasma jet" where TPS samples and probes are tested. Depending on the mass flow of gas injected, static pressures as low as 10 mbar can be maintained in the test chamber. A typical working condition with a power setting 3 kW, gas flow of 0.5 g/s, and static pressure of 20 mbar is shown on figure 9.

A sketch of the facility is presented in figure 10. The test chamber, exhaust system, generator and pump as well as the different part of the set-up are also represented

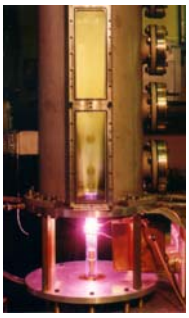

Fig. 9 : VKI Minitorch in operation

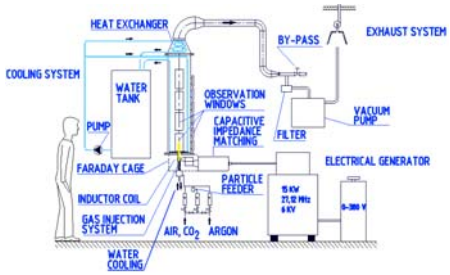

Fig. 10 : The VKI Minitorch facility

The VKI Minitorch facility allows to combine particle erosion and aero-heating test.

In this case a particle injection device is added to the plasma torch [18].

The method of particle injection is to entrain particles into a carrier gas and accelerate this particle-gas mixture through a convergent-divergent nozzle. The nozzle exit is situated in the center of the top of the inner-block. It produces a stream of high speed particles which would impinge on a TPS sample placed in the test chamber. Typical particle velocities of 300 m/s have been measured by LDV in air and CO2 plasma conditions [19]. In order to simulate the particle erosion phenomena in this ground facility the mass of the particles injected are adapted to match the particle kinetic energy involved in a Martian entry situation.

Most important for Martian applications, this facility can perform tests with CO2. Its main limitation lies in the relatively moderate particles velocities and test mock up dimensions.

8.2. SIMOUN facility

SIMOUN facility was dimensioned to meet space plane and re-entry mission simulation requirements, for European Space Programs.

The main simulation parameters are heat flux densities (related to the surface temperature),

pressure (static or total) and mission duration (see table 2).
The facility (figure 11) includes three main subsystems:
First, the plasma generator, which is a standard module based on Huels technology and adapted to provide the stagnation pressure (PI) and the stagnation enthalpy (HI/RT0) needed for correct nozzle operation.

Figure 11: SIMOUN plasma generator

Second, the aerothermal tunnel, which consists in a supersonic nozzle, a test chamber and a convergent-divergent diffuser tube. Two nozzles are currently used to cover all of the operating fields:

- one circular nozzle of revolution for "stagnation point" tests
- one super elliptical nozzle (with flat surface extended by the plate of material), for the "flat plate" tests.

The flow - homogeneous and satisfying the required conditions - enters the test chamber as a "free jet". The test chamber is 1 m diameter and 1 m long. It includes four doors, three of which are equipped with windows for optical viewing (temperature measurements and visualizations), and one in lower part that supports the test set-ups.

Stagnation point	Flat plate
circular nozzle	super elliptical nozzle
S_c = 5.4 cm^2	S_c = 7 cm^2
specimen : - hemispherical, diameter 50 mm - flat	specimen : 420 x 340 mm^2 x 120 mm thick
p'_i = 3 to 40 kPa	p_e = 0.3 to > 10 kPa
$\dot{q}$ = 400 to 4500 kW/m^2 on flat cold wall	$\dot{q}$ = 50 to 1600 kW/m^2

Table 1 : Simoun facility performances function of the test technique

Work pressure pi	100 to 1,700 kPa
Reduced enthalpy hi/RT0	40 to 170
Gas mass flow rate	30 to 700 g/s
Duration	Up to 1,500 s

Table 2: Simoun main characteristics

To account for dust flow assessment, the power injection on SIMOUN facility is based on the powder injection knowledge obtained on previous study. Indeed, this technique has been developed on AQTIL facility **(**an other EADS experimental facility, **patent 05/50693)**, which is now qualified for high erosion TPS characterization (See AQTIL plasma torch description). Several complementary diagnostics have been implemented (particle homogeneity, particle velocity, erosion rate determination) and are now available for TPS erosion tests.

SIMOUN is presently operational with air or CO2 gas flows.

9. SIMULATION TOOLS

As neither of the ground tests facilities available can provide a full simulation of the high speed reentry in dusty atmosphere, assessment of TPS response must rely on computational simulations. The main issue is to have a full set of validated models to account for all phenomena listed in preceding paragraphs. The complexity of this task clearly appears when we compare program flowcharts with clear or dusty atmosphere (Fig 12 and Fig. 13).
In fact, in many cases, it is necessary to cut some corners in order to get a full assessment of dusty flows. For example, the mass decrease of particles during shock layer crossing is usually taken as zero, in order to have a pessimistic assumption to cover real situations that are difficult to handle (mainly because dust particles nature is uncertain, as well as sizes and demise phenomena).
Dust erosion parameters are also difficult to obtain for many reasons, the main one being that there is no ground test that can simultaneously take into account multiple impacts, high velocities and temperature effects.
Keeping in mind all these unresolved problems, we have nevertheless developed design tools that help taking dust effects on TPS design. Some results are presented on Fig 14.
A more comprehensive description of simulation tools can be found in [16]

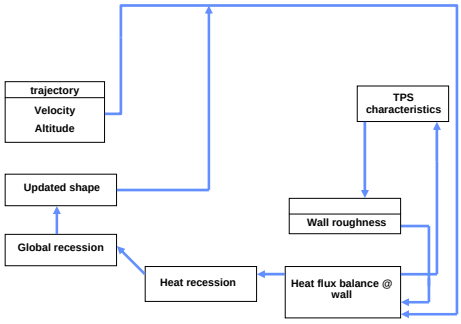

Fig. 12 : simplified clear atmosphere heat recession simulation flowchart

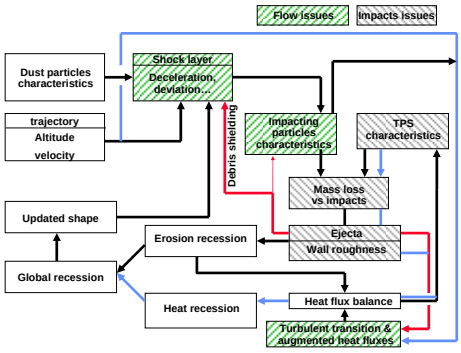

Fig. 13 : simplified dusty atmosphere heat recession simulation flowchart

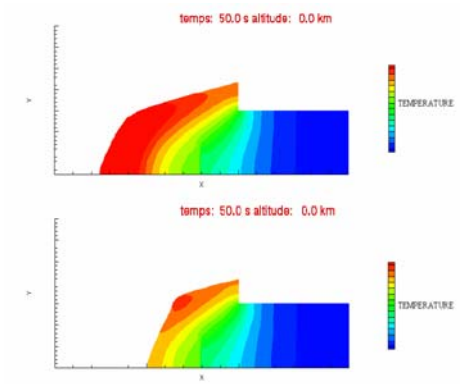

Fig.14 : example of recession computation without and with dust in the atmosphere

10. Discussion

According to preceding chapters, it appears that the assessment of dust effects on high speed vehicles entry in Mars atmosphere involves many unique physical phenomena, most of which should need careful modelling to make a proper design of the vehicle TPS. Models are effectively available. The main issue is to have a comprehensive and homogeneous set of models of all phenomena. In fact, we do not consider that we have today such models, which often leads to define a so called "erosion provision" for TPS design. The consequence can be an over specification of TPS thickness, and it is thus important to identify the main sources of uncertainties.

First and most important one is probably the dust scenario specification. The uncertainties on that topic are comparable to those on the clear atmosphere column upon arrival on the planet. The usual way to cope with this issue is to set high values of τ, which seems comfortable from the end user point of view, but can be inconsistent with other vehicle specifications. For instance, large dust content generally coincides with large deviations of local atmosphere density from clear air situation. This means that, for instance, vehicle breaking history can be significantly affected, and "ordinary" reentry issues may supersede dust effects.

Second in order is the difficulty to obtain reliable hot charred material response to multiple impacts. Though many ground facilities are available, as we have seen, their limitations (either velocity or temperature) are still important, and good impact modelling and material behaviour modelling are the only alternative to overcome these limitations.

Third uncertainty is the flux modifications due to particles presence. Transition triggering due to increased roughness can be handled with bearable over specification by using high values of roughness in usual "roughness dominated transition models". Heat fluxes modifications attributed to flow perturbations seem more complicated to assess as the increase is rather scattered among references. This is probably the main troublesome issue as "non roughness-related" heat fluxes increase are no doubt since they have been evidenced with smooth mock-up in seeded flow wind tunnel tests. Today however, a ratio dusty flow/non dusty heat fluxes around 2 seems more supported by experimental evidence than alleged ratio of 6 and more.

Other effects (debris shielding, shock crossing effects…) are less known and modelled, and thus are prone to bring large uncertainties.

For instance, modelling of particles transformation and deviation in the shock layer requires good knowledge of particles properties (nature, shapes, heat exchange with surrounding flow, drag coefficients…). However, if present models and parameters available can be used for a sensitivity assessment of shock layer crossing influence, they are not sufficiently validated and relevant (only sphere drag is documented enough to perform such assessment [17]) to prevent using the crude assumption of "no demise, no deviation, no breaking" in the TPS sizing.

So are the other effects, which we usually account for with the more conservative assumptions possible to be sure to cover all situations. Fortunately, these conservative assumptions have generally less effects on final TPS sizing than the uncertainties on the three main issues discussed previously (dust scenario, material response and heat fluxes increases), which prevents irrelevant erosion provisions.

11. CONCLUSIONS

We have proposed a review of dust effects on Martian re-entries, with a focus on available modelling tools and test facilities. Though probably all the phenomena occurring have been identified, many still stay with little mean to model them or to perform ground test to access to all the physics and parameters.

It does not seem that ground tests can easily reproduce all the phenomena (erosion, heat flux increases, roughness modification, charring) at the same time. So, we favour separate ground assessment of all these effects, and rely on careful modelling to account for the coupling of the various effects.

In our opinion, dust impact material response at high temperatures is the main phenomena to address in importance vs TPS sizing, and many ground tests facilities and simulation tools are available thus for.

Heat fluxes augmentation and roughness modification are our following concerns. Other issues should not be neglected however, but accessing to the detailed physics is probably neither a short term nor an easy task : as they can be covered with conservative assumptions for TPS design, they are granted less modelling effort than other issues.

Most important uncertainty is however the dust content scenario to withstand. This problem is beyond the scope of this paper, but nevertheless the main driver in dust risk assessment.

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