DEVELOPMENT STATUS OF POWERED DESCENT FOR HIGH-MASS MARS ENTRY, DESCENT, AND LANDING SYSTEMS

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ABSTRACT

Retropropulsion, initiated at supersonic conditions, provides both deceleration and control authority as an enabling capability for the delivery of human-scale payloads to the surface of Mars. There are no other presently viable approaches to the descent phase of flight for vehicles of such scales. NASA continues to dedicate investment in the maturation of powered descent in atmospheric environments, for the express application to large-scale entry, descent, and landing systems. Efforts focus on parametric, subscale, inert gas ground testing, rigorous validation of computational modeling approaches against these data, and the implementation of highly efficient, scalable simulation tools. This paper summarizes the current maturity of retropropulsion in a free-flight, atmospheric environment for vehicles with significant aerodynamic surface area, as well as the current status of efforts within NASA for ground testing, computational simulation, and flight testing.

Index Terms— Retropropulsion, Aerodynamics, EDL, CFD, Ground Testing

1. INTRODUCTION

Retropropulsion, initiated at supersonic conditions, is the only presently viable approach to the descent and landing of human-scale payloads on Mars, providing both deceleration and control authority for precision landing. Propulsive deceleration is accomplished by directing rocket engine exhaust against the oncoming freestream flow, and this powered phase of flight is generally continuous from engine initiation through to landing. While retropropulsion is now frequently used to recover launch vehicle stages, engine characteristics closer to in-space propulsion and significant vehicle aerodynamic surface area present challenges unique to the Mars descent application of powered flight. Similarly, powered descent and landing at the Moon does not retire aerosciences risk due to the lack of atmosphere [1]. For infusion into future missions, supersonic retropropulsion (SRP), or powered descent, will require significant maturation beyond the present state-of-the-art for ground test data, computational modeling, and flight testing [1, 2].

Retropropulsion significantly alters the flowfield upstream of the decelerating vehicle, with the potential to change the aerodynamic forces and moments experienced by the vehicle [3]. The nozzle expansion condition (over-expanded vs. under-expanded), the number and placement of nozzles on the vehicle, vehicle attitude, and local atmosphere conditions along the descent trajectory all have the potential to change the stability and control of the vehicle during powered flight (see Fig. 1). The principle technology challenge for powered descent remains the characterization and reduction of uncertainties associated with both aerodynamics and aerothermodynamics arising from the interaction of the vehicle and retropropulsion engine exhaust with the oncoming atmosphere in flight [1, 4].

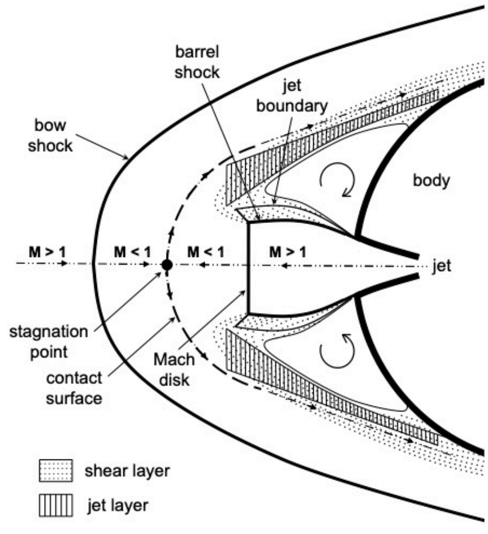

Fig. 1. Retropropulsion flowfield features for supersonic conditions [3]

There is currently no human-rated vehicle relying on retropropulsion for descent and landing in an atmospheric environment. Continued development of powered descent for atmospheric environments is enabled by progressive balanced investments in ground testing, predictive computational capabilities, and flight testing and demonstration. This paper outlines the present status and major challenges for advancing the component technologies of supersonic retropropulsion and predictive capabilities such that reliable mission infusion is attainable for the order of magnitude increases in landed mass required for human Mars exploration. Component technologies include large engines (100s of kilonewtons of thrust) capable of throttling and gimbaling, entry vehicle aerodynamics and aerothermodynamics modeling, entry vehicle stability and control methods, reference vehicle systems engineering and analyses, and high-fidelity models for entry trajectory simulations. An updated development roadmap is presented that includes technology gates that are achieved through ground-based testing and high-fidelity analysis, with subscale flight testing in Earth's atmosphere to demonstrate stable and controlled flight as well as to provide critical free-flight data for comparison with six degree-of-freedom trajectory analyses. While no notional schedule is proposed, this paper advocates for continued investment and increased international collaboration for advancing the fundamental capability from expanded ground testing data products to suborbital free-flight tests at Earth through larger and more complex system-level technology demonstration and consideration of a precursor mission at Mars.

2. TECHNICAL MATURITY AND KEY CHALLENGES

Maturing atmospheric powered descent challenges traditional processes and dependencies in entry system design, as the boundaries between classic disciplines are no longer as concrete as they can be with Viking-heritage entry systems [1]. Changes to a design by one discipline have a greater potential to affect overall vehicle performance than in the case of powered descent with no atmosphere or in the case of a vehicle with more discrete phases of flight, such as a capsule with a parachute. The interdependence arises from the sensitivity of propulsive-aerodynamic interference effects to small changes in retropropulsion, or vehicle, configuration and the operational environment. The counterbalance of system performance across numerous elements in the Mars exploration architecture and a desire to minimize the number of component and subsystem developments across these elements has yielded retropropulsion conditions and designs that are no longer as flight-relevant as such conceptual designs were a decade ago. Conceptual designs produced from now higher-fidelity analyses do not necessarily yield the lowest aerosciences uncertainties during powered descent.

NASA uses Technology Readiness Levels (TRLs) to systematically define progressive levels of technical maturation, from the observation of basic principles (TRL 1) through successful application on a spaceflight mission (TRL 9) [5]. Table 1 defines the NASA TRLs, now largely standard across government and academia. NASA uses TRL as one metric for determining the readiness of a technology for its intended purpose, as well as in measuring progress attained through focused investment. Commonly, technologies must be at or near TRL 6, which requires demonstration in relevant environment, if not also at relevant scale and system complexity, prior to mission infusion, where then the adopting program fully integrates the technology to satisfy mission requirements and completes flight qualification. For powered descent, achieving TRL 6 will require Earth-based, subscale flight testing to demonstrate aerodynamic performance, as well as acceptable control authority to maintain stable flight, with additional validation data for computational modeling.

Table 2 summarizes key technology challenges for powered descent and their estimated current TRL. Component technologies and systems for rocket propulsion, aerodynamics/aerothermodynamics, and guidance, navigation, and control (GN&C) have specific challenges to the human-scale Mars lander application. Systems analysis and integrated vehicle design and performance will always be limited by the fidelity of the underlying models. The combination of ground testing, computational simulation, and flight testing is required, while it is understood that for vehicles of such scale and complexity as a human-scale Mars EDL system, there will be a stronger reliance on computational simulation to develop and eventually certify powered descent for mission infusion.

3. SUMMARY OF CURRENT PROGRESS

Powered descent trajectory simulations initially assumed negligible aerodynamic contributions for simplicity or due to a lack of knowledge. More recently, aerodynamics models derive from wind tunnel testing and/or computational flowfield analyses. As the fidelity of these vehicle performance assessments has increased, conditions and designs with the lowest perceived aerosciences risk are no longer as flight-relevant, continuing to motivate investment in the validation of computational fluid dynamics (CFD) methods against more relevant test data than available in the historical literature. This section describes the present status of NASA efforts in ground testing, computational modeling and simulation, and flight testing for powered descent.

3.1. Ground Testing

Powered descent ground testing at NASA remains limited to subscale, inert gas testing conducted in supersonic wind tunnels. Simulant gases continue to be predominantly air. An upcoming test campaign in the NASA Langley Unitary Plan Wind Tunnel, a 4 × 4 foot closed-circuit supersonic wind tunnel, will test at least 7 different retropropulsion configurations across freestream Mach numbers from 2.4 to 4.6, sweep angle of attack, and include nozzle pressure ratio variations sufficient to investigate transitions between over-expanded and under-expanded nozzle flows. Figure 2 shows the model con-

Table 1. NASA technology readiness levels 1 through 6 (out of 9) [5]

TRL	Definition	Description
1	Basic principles observed and reported	This is the lowest ”level” of technology maturation. Scientific research begins to be translated into applied research and development.
2	Technology concept and/or application formulated	Practical application of those characteristics observed at TRL 1 can be “invented” or identified. The application is still speculative; there is not experimental proof or detailed analysis to support the conjecture.
3	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development (R&D) is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory-based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute “proof-of-concept” validation of the applications/concepts formulated at TRL 2.
4	Component and/or breadboard validation in laboratory environment	Basic technological elements must be integrated to establish that the “pieces” will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must be devised to support the concept that was formulated earlier, and it should be consistent with the requirements of potential system applications.The validation is relatively “low fidelity” compared to the eventual system; it could be composed of *ad hoc* discrete components in a laboratory.
5	Component and/or breadboard validation in relevant environment	The fidelity of the component and/or breadboard being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component level, subsystem level, or system level) can be tested in a “simulated” or somewhat realistic environment.
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	A representative model or prototype system or system must be successfully be tested in a relevant environment. At this level, if the only “relevant environment” is the environment of space, then the model/prototype must be demonstrated in space. Not all technologies will undergo a TRL 6 demonstration; at this point, the maturation step is driven more by assuring management confidence than by R&D requirements.

Table 2. Key technology challenges (updated from [2]

Technology (estimated TRL)	Major Challenges	State-of-the-art
Rocket propulsion (TRL 4+)	1) Development of large engines (hundreds of kN of thrust) capable of deep throttling and/or gimbaling	1) Conceptual engine and propellant tank sizing for a 20t payload [6]
	2) Development of long-term cryogenic propellant storage or viable ISRU production	2) Analysis of long-term propellant storage
Aerodynamics and Aerothermodynamics (TRL 3)	1) Prediction of aerodynamics (static and dynamic forces and moments) and aerothermodynamics (surface heating)	1) Cold-gas wind tunnel testing across broad range of parameters and configurations [3, 4, 7]
	2) Development and validation of CFD tools to build aerodynamics and aerothermodynamics databases	2) Navier-Stokes CFD solutions show promising agreement with cold-gas wind tunnel test data and qualitative agreement with limited launch vehicle return flight data [8, 9, 10, 11, 12, 13]
GN&C (TRL 3)	1) Development of algorithms and systems to control and stabilize the entry vehicle in the presence of complex aerodynamics-propulsive interactions	1) Closed-loop NPC guidance and closed-loop control via 6-DOF simulations [6, 14]
Systems engineering and analysis (TRL 3)	1) Definition of reference vehicle configurations	1) Conceptual vehicles, engines, and sizing for a 20t payload [6]
	2) Configuration and packaging of SRP engines on full-scale reference vehicles to meet system performance and packaging requirements	2) 6-DOF trajectory analysis demonstrating enabling performance with SRP [6, 14]
	3) Test and analysis for plume-surface interaction effects during landing	
	4) Development and validation of high-fidelity models required for integrated EDL trajectory simulations	
Ground testing (TRL 3)	1) Testing completed in ground facilities that can achieve relevant environments for engine, aerodynamics, and aerothermodynamics experiments	1) Wind tunnel testing [7, 15, 16]
	2) Database creation for validation of analytical methods (e.g. CFD)	2) Small-scale engine testing
		3) Conceptual design of a hot-fire engine test [17]
Flight testing (TRL 2 to 7+)	1) Completing stable and controlled instrumented flight testing with as-predicted performance at sufficient scale and complexity to reduce risks for the desired mission infusion scale	1) Conceptual design of suborbital Earth free-flight tests [17]
		2) Commercial launch vehicles with minimal aerodynamic surface area routinely use SRP for first stage booster recovery [18]

figurations to be tested. For the first time, both pressure sensitive paint and a new 6-component flow-through balance will be used to obtain force and moment data, along with discrete steady and unsteady pressure measurements, high-speed schlieren flowfield imagery, and a novel oil seeding technique for additional flow visualization. This campaign will be a significant augmentation to the prior supersonic wind tunnel test efforts by NASA in 2010 [15] and 2011 [16], with explicit objectives to deliver data for the validation and uncertainty quantification of state of the art CFD methods for powered descent supersonic aerodynamics.

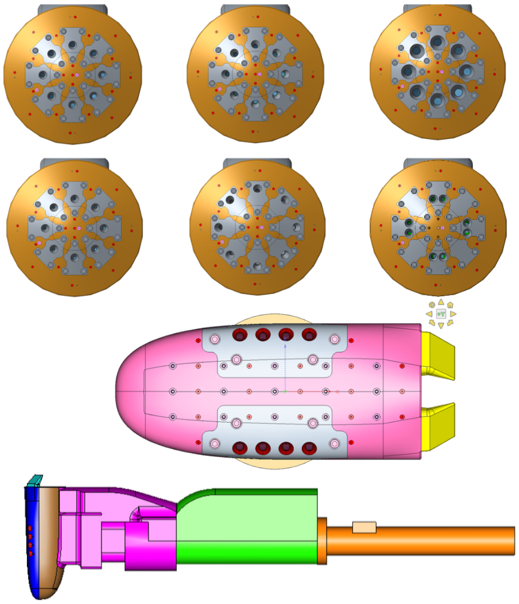

Fig. 2. Wind tunnel models upcoming testing [7]

Inert gas testing continues to be highly valuable, but there are unavoidable limitations when using air as the plume simulant gas and low temperatures. Future testing with different simulant gases, such as heated ethane, and with a hot-fire propulsion test article is becoming increasingly necessary to both provide more relevant validation data for aerodynamics and aerothermodynamics and to quantitatively characterize the limitations or potential extensibility of testing and validation activities with inert gas data. As powered descent is a continuous phase of flight from engine initiation through to landing for the human-Mars application, data are also needed at transonic and subsonic conditions, as well as a much greater variation in Reynolds number to account for limitations in length scales and model sizes in ground test facilities [4].

3.2. Computational Modeling and Simulation

Aerodynamic interference during powered descent challenges even the highest fidelity CFD approaches with unsteady turbulent free shear layers, strong shocks, non-equilibrium chemistry, entrainment, complex geometry, and large domains. Over the past decade and a half, CFD tools have demonstrated an ability to capture most major flowfield features and behavior, within the limited available validation data from subscale, inert gas ground testing [15, 16]. The largest differences between computational codes and also with modeling approach arise in the near-body regions around the nozzle exits and for configurations with multiple nozzles. The upcoming NASA supersonic wind tunnel test effort described in the prior section will provide the first significant parametric data set for multiple-nozzle retropropulsion configurations. The CFD campaign associated with this test will further benchmark the status of Navier-Stokes solvers in a production mode to predict multi-nozzle retropropulsion aerodynamics at subscale with inert gas simulants and to support rigorous uncertainty quantification.

The most advanced NASA CFD solutions for retropropulsion using tools validated against subscale inert gas wind tunnel test data are applying detached eddy simulation (DES) approaches at full scale, with and without finite rate chemistry, and with massively parallel execution on GPUs [9, 19]. Figure 3 shows instantaneous Mach number and vorticity magnitude contours from this recent work. Requirements for accurate prediction still include very large computational domains, lengthy temporal solution durations, and high-fidelity methods geared towards the capture of strong shocks and free shear layers. No validation data presently exist within NASA for retropropulsion below Mach 1.4, though recent works have extended solutions down to Mach 0.8 applying prior best practices [20, 21]. Reynolds Averaged Navier-Stokes (RANS) methods are still regularly applied to this problem, largely due to computational resource limitations, generally good agreement with test data under limited conditions and configurations, and the inability of most codes to execute on GPUs [22, 23, 24]. Exploratory work with LES methods, with and without wall models, has also been completed with varying degrees of comparison to existing test data [10].

The inability to directly simulate the Martian retropropulsion environment through either ground or flight testing at Earth necessitates a heavy reliance on high-fidelity computational approaches to predict aerodynamic-propulsive interference. The databases required to characterize powered descent vehicle performance are highly parametric, with the eventual flight aerodynamics databases requiring hundreds or thousands of simulations. A significant challenge remains in defining and demonstrating a comprehensive approach to the development of these databases, where tools and data products of varying fidelity and degrees of uncertainty are collectively utilized to define retropropulsion-induced environments during this phase of flight.

Very minimal validated work exists at present for the aerothermal environments induced by retropropulsion, and the operational envelope for powered descent is well past that driving thermal protection system design during entry. It is

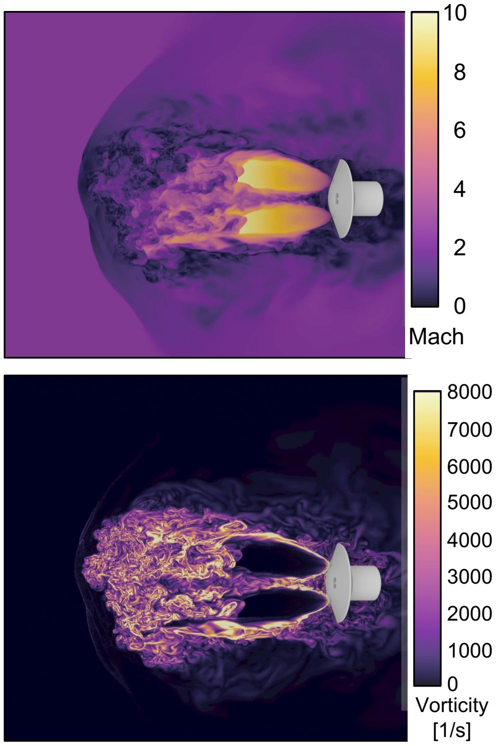

Fig. 3. Retropropulsion flowfield solutions from DES (upper - Mach number; lower - vorticity magnitude) at Mach 2.4 freestream [20]

anticipated, though not yet demonstrated, that computational approaches capable of accurately predicting the complex flow structure and behavior during powered flight and in predicting plume-induced heating for other applications will be extensible to the prediction of aerothermal environments during powered descent [18, 25, 26]. The maturation of computational modeling and simulation for retropropulsion continues to require additional ground test data, notably from testing with different simulant gases and with high-enthalpy, larger-scale propulsion elements.

3.3. Flight Demonstration

The state of the art in flight demonstration and full-scale application remains the now-routine and prominent use of retropropulsion for the deceleration, targeting, and soft landing-recovery of first stage launch vehicle boosters by commercial companies. While launch vehicles lack the aerodynamic surface area of exploration entry systems, these successful flights have largely resolved questions on engine ignition in a comparable-momentum opposing flow, demonstrated control of multiple high-thrust engines in a retropropulsion mode, and provided the first available data on such plume-induced aerothermal environments [18].

Launch vehicles, particularly the first stage, tend to operate with lower nozzle expansion ratios and higher thrust-force coefficients, in addition to having minimal aerodynamic surface area in the deceleration direction. These characteristics make launch vehicles particularly well-suited for retropropulsion, with aerodynamic-propulsive interference resulting from the operating conditions now proven to be manageable with control and stability margins that are not detrimental to the primary capabilities of the vehicle as a launcher. As discussed in Ref. [1], retropropulsion-induced aerodynamics and aerothermodynamics on EDL performance, as well as system-level impacts of discipline-specific design choices, are affected by a broader parameter set than are consistently present in the launch vehicle application. Under conditions and configurations where retropropulsion operation is closer to a launch vehicle first stage than a high-drag entry system, CFD simulations more consistently agree well with available subscale, inert gas ground test data.

This decade will include numerous landing attempts on the Moon, with vehicles of widely varied configurations, operations, and scales, all of which require a propulsive descent and landing phase. Due to the lack of an atmosphere, however, powered descent at the Moon does not reduce the risks associated with aerodynamic-propulsive interference for large-scale Mars landing systems. Lunar landers will provide valuable experience for future Mars-focused vehicles through integration and demonstration of several challenges listed in Table 2, including long-term cryogenic propellant storage, deep throttling engines, GN&C with retropropulsion in the absence of atmosphere, and near-field plume-surface interaction effects. Due to the significant aerosciences differences between launch vehicle and Lunar lander retropropulsion and the human-scale Mars retropropulsion application, a robotic-scale precursor may be required to reduce the overall risk to the full human-scale mission implementation.

4. CONCLUSIONS

NASA is continuing investment in ground testing and computational simulation to mature powered descent for atmospheric environments. The target mission application is for human-scale Mars entry, descent, and landing systems, requiring continued exploration of multiple nozzle configurations on vehicles with significant aerodynamic surface area. Upcoming ground testing will use high-pressure air as the simulant exhaust gas for multi-nozzle models in a supersonic wind tunnel, with objectives to progress to testing with other simulant gases and a hot-fire test article. Evaluation of computational modeling approaches of varying fidelity against ground test data continues, with particular emphasis on the effects of turbulence modeling and chemistry. Ultimately, flight data will be necessary to support mission infusion of powered descent.

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