Simulation of Liquid Injection Thrust Vector Control for Mars Ascent Vehicle

Jared Gudenkauf[1]
Jacobs ESSSA Group, Marshall Space Flight Center, Huntsville, AL 35808

The Jet Propulsion Laboratory is currently in the initial design phase for a potential Mars Ascent Vehicle; which will be landed on Mars, stay on the surface for period of time, collect samples from the Mars 2020 rover, and then lift these samples into orbit around Mars. The engineers at JPL have down selected to a hybrid wax-based fuel rocket using a liquid oxidizer based on nitrogen tetroxide, or a Mixed Oxide of Nitrogen. To lower the gross lift-off mass of the vehicle the thrust vector control system will use liquid injection of the oxidizer to deflect the thrust of the main nozzle instead of using a gimbaled nozzle. The disadvantage of going with the liquid injection system is the low technology readiness level with a hybrid rocket. Presented in this paper is an effort to simulate the Mars Ascent Vehicle hybrid rocket nozzle and liquid injection thrust vector control system using the computational fluid dynamic flow solver Loci/Chem. This effort also includes determining the sensitivity of the thrust vector control system to a number of different design variables for the injection ports; including axial location, number of adjacent ports, injection angle, and distance between the ports.

Nomenclature

LITVC	=	Liquid Injection Thrust Vector Control
MAV	=	Mars Ascent Vehicle
MON	=	Mixed Oxides of Nitrogen

[1] Computational Fluid Dynamics Engineer, MSFC Propulsion Group (ER42). Member AIAA

I. Introduction

II. Mars Ascent Vehicle Description

The MAV design team has performed many trade studies on the best type of rocket motor from the options of either solid, liquid, or hybrid motors; the hybrid study resulted in the best fit for the mission to Mars. Long duration storage of the MAV at the wide range of Marian temperatures, ability to restart the motor, long burn time, and overall rocket size being the main drivers toward the hybrid motor selection for the mission.

The fuel the hybrid motor is a paraffin wax based solid called SP7 which will use the oxidizer that is a Mixed Oxide-Of-Nitrogen (MON 30). MON30 consists of seventy percent nitrogen tetroxide (NTO) and thirty percent nitrogen dioxide. MON30 was selected because of its low freezing temperature (193 K) versus that of NTO (262 K); thus lowering the heating requirement during storage on Mars. The properties of NTO and MON30 are detailed later in this paper.

To lift-off of the surface of Mars and guide the vehicle into the prescribed orbit around Mars requires the MAV to have a method of achieving thrust vector control. A number of different options exist for controlling a rocket in the low pressure (~700 Pa) that is present on Mars but the lightest weight option was determined to be the use of a fixed nozzle that injects liquid oxidizer into the supersonic portion of the nozzle to deflect the thrust; this is referred to as liquid injection thrust vector control (LITVC). There are a couple of rockets that use a LITVC system, with the most notable being the Minuteman II second-stage and Titan III solid rockets. The table below summarizes the current design of the MAV motor (Ref 1).

Table 1: MAV Hybrid Motor Design Parameters

	Value
Fuel/Oxidizer	SP7/MON30
Oxidizer to Fuel Ratio	4.56
Isp (95% efficiency)	317 s
Chamber Pressure	250 psia
Nozzle Area Ratio	40
Thrust Vector Control	Liquid Injection

III. Liquid Injection Thrust Vector Control Description

The injection of a liquid in the supersonic section of the rocket nozzle creates a large oblique shock that produces a side force on the side of the nozzle. The figure below illustrates a basic concept for the LITVC system.

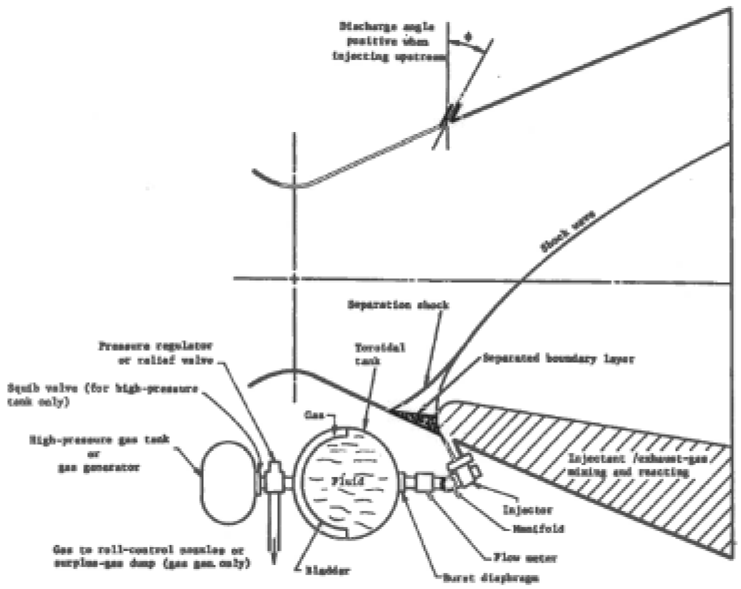

Figure 1: Schematic of Typical LITVC System and Side Force Phenomena (Ref 2)

IV. Simulation Methodology

The computational fluid dynamic (CFD) flow solver Loci/Chem was used to perform the calculation for this paper. This section will outline the capabilities and highlight the new capabilities required for this analysis.

A. Tabular Equation of State Model

B. Cavitation Model

V. LITVC Port Design and Sizing

The port, or orifice, that the liquid for the LITVC system flows through must be designed to maximize the velocity for a given flowrate but yet prevent cavitation of the liquid inside the port. Unlike vapors which by their very nature are compressible and can be squeezed through a large range of port sizes and liquid will begin to cavitate when the static pressure in the liquid reaches vapor pressure.

$$P_{static} = P_{vapor} \qquad \text{(Equation 1)}$$

When a liquid cavitates bubbles of a vapor and liquid mixture quickly form and collapse, the velocity of which is supersonic due to the extremely low speed of sound in the mixture, and this collapsing bubble can damage the valve and port. The following two figures illustrate the damage caused on different types of values due to the cavitation of water.

Figure 2: Valve damage due to cavitation of water (Ref 3)

As it is evident that the cavitation destroys the seating surfaces of the valve which makes the valve impossible to seal and therefore leakage will occur. To prevent cavitation around the valve and within the LITVC port the following method was used.

The total pressure of an incompressible fluid can be calculated from Bernoulli's equation:

$$P_T = P_S + P_D \qquad \text{(Equation 2)}$$

Where: P_T = Total Pressure
P_S = Static Pressure
P_D = Dynamic Pressure

The dynamic pressure is:

$$P_D = 0.5*\rho*V^2 \qquad \text{(Equation 3)}$$

Where: ρ = Density
V = Velocity

Substituting equation 3 into equation 2 and using the knowledge that the static pressure must be kept at or above the vapor pressure the maximum velocity of the liquid can be found by the following equation:

$$V_{Max} = \sqrt{{(P_T\text{-}P_V) * 2}/{\rho}} \qquad \text{(Equation 4)}$$

VI. Analysis

A total of 12 different models were built to determine the sensitivity of the thrust vector produced by the LITVC system for a number of independent design variables. These design variables include axial position, the total number of ports, the injection angle, and the distance between the LITVC ports. Also explored is the sensitivity of thrust vector angle with mass flow rate of the port, as a percentage of maximum flow rate, and rate of evaporation in the cavitation model. The table below outlines each of the independent design variables for each of the different CFD models.

Table 2: CFD Models Used for Sensitivity Analysis

Case Num	# Ports	Position	Injection Angle	Port Sep Angle
		x/L	(Deg)	(Deg)
1	1 Port	0.34	0	0
2	2 Port	0.34	0	5.5
3	2 Port	0.34	0	11
4	3 Port	0.34	0	5.5
5	3 Port	0.34	7.5	5.5
6	3 Port	0.34	15	5.5
7	3 Port	0.267	0	5.5
8	3 Port	0.447	0	5.5
9	3 Port	0.267	7.5	5.5
10	3 Port	0.447	7.5	5.5
11	3 Port	0.34	0	5.5
12	3 Port	0.34	0	5.5
13	1 Port	0.34	0	0

Conclusions

Acknowledgments

References

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