INDIGENOUS CARBON DIOXIDE AS A PROPELLANT FOR MARS SURFACE PROBES

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ABSTRACT

We have investigated the performance of supercritical carbon dioxide as a candidate for Mars surface propulsion operations. Since Mars dry ice can be frozen out of its atmosphere and confined subsequently in a fixed volume with relative ease, the modest critical temperature and pressure of carbon dioxide can be exploited by heating the captured dry ice at constant volume. The research reported here has measured the specific impulse behavior of impure supercritical carbon dioxide produced by heating confined dry ice in a pressure vessel to temperatures up to 74 °C, followed by blow-down expansion of the resulting supercritical fluid through a supersonic Mach 2 nozzle. By varying the mass of the dry ice charge and initial temperature, it was possible to produce three types of blow-down processes. Short-duration specific impulse peaks ($I_{sp} \approx 100$ sec) were observed for all three types of blow-down process, and the measured extended-duration specific impulse was $I_{sp} \approx 40$ sec. Optimal performance was produced when blow-down proceeded through the condensing, two-phase flow regime.

1. INTRODUCTION

Currently, Mars surface exploration is restricted to relatively flat terrain in close proximity to the Mars rover landing sites. When surface mobility is restricted to autonomous rovers, these slow-moving, low-powered vehicles cannot open up larger regions for exploration. Therefore a surface transportation system is needed that can move rapidly, traversing difficult terrain, in order to achieve expanded science objectives within a much shorter time. A "hopper" is such a system. A hopper is a vehicle that uses rocket propulsion, achieving a ballistic flight path over any type of terrain, to reach a prescribed destination. Carbon dioxide is of particular interest for use as a Mars surface propellant due to its abundance in the atmosphere. Unlike propellants that must either be transported from Earth or acquired from a fixed fuel production site, a carbon dioxide-propelled hopper is capable of refueling itself by simply freezing dry ice out of the Martian atmosphere. When that ice is confined in a fixed volume and heated to supercritical conditions, a high stagnation pressure can be obtained at modest temperatures. Hence, it is possible to consider pressurized carbon dioxide for propelling Mars surface probes when they incorporate solar cells, a thermoelectric heat pump (to condense, then heat the carbon dioxide) a pressure tank and nozzle system. However, that type of probe propulsion can only be given serious consideration when its performance is better understood and demonstrated experimentally.

Using the method of characteristics for a non-ideal gas, Blass [1] and coworkers [2] designed a supersonic Mach 2 nozzle and test apparatus to measure the blow-down thrust performance of supercritical carbon dioxide as a candidate for Mars surface applications. Unfortunately, fabrication difficulties were encountered and thus far, only sonic nozzle performance has been reported [2]. Those tests appeared to show that sonic carbon dioxide gas expansion could be sustained into a subcooled flow regime, thereby improving propulsive performance. However, the tests also showed that heating from the pressure vessel had contributed to the thrust performance. While modest heating via solar energy can be leveraged using the assumed thermoelectric heat pump for Mars surface applications, it was necessary to properly account for the pressure vessel heating during these experiments. The work reported here has successfully fabricated a supersonic nozzle test article, and greatly improved the test cell operation and associated instrumentation, permitting determination of specific impulse performance of supercritical carbon dioxide under supersonic blow-down conditions that can be achieved on the Martian surface.

Recently, blow-down performance of supercritical carbon dioxide has been under investigation because of its possible use in advanced nuclear power plant designs [3,4]. Those studies affirmed the fact that the thermodynamic and thermophysical property behavior of supercritical carbon dioxide varied so rapidly that computational models were unreliable in predicting flow rates and performance.

The behavior of the CO_2 propellant during blow-down thrust operation is highly-dependant on the initial conditions. Mignot, Anderson, and Corradini [4] have identified three initial condition regions that produce different blow-down flow behavior. As depicted in Figure 1, blow-down through Region 1 produces a subcritical superheated vapor; Region 2 produces a condensing two-phase mixture, while Region 3 produces a vaporizing two-phase mixture. Since the sonic experiments suggested the possibility of subcooled nozzle performance, all three initial condition regions could be relevant. The characterization of the performance of a supercritical carbon dioxide thruster will rely heavily on these experimental results and the experimentally obtained properties. The purpose of this study is to characterize the thrust and specific impulse performance of such a thruster in the different operational regions in order to optimize performance for Mars surface applications.

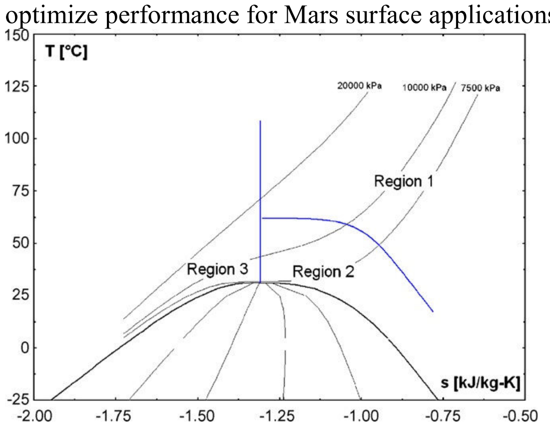

Fig. 1. T-s diagram for CO_2 showing blow-down regions

2. EXPERIMENTAL SET-UP

The supercritical CO_2 thruster unit is shown in Figure 2. Commercially-available dry ice was used to charge the pressure tank and no effort was made to remove the small amount of condensed water ice and residual air that remained in the pressure vessel, treating those molecules as surrogates for Mars atmospheric non-condensables. After the pressure tank was charged with a specific mass of dry ice, the flanged end cap with O-ring seal was secured and the tank assembly was installed in the test apparatus, shown schematically in Figure 3. The basic test apparatus employed in the earlier sonic blow-down experiments [2] was utilized here. However, the specific impulse of the propellant must be calculated using the measured thrust and associated propellant mass flow rate, and the actual behavior of the supercritical fluid upstream from the nozzle was a concern. The original test stand utilized a low-friction linear bearing sliding rail system, aligned in the thrust direction with a calibrated load cell to measure the instantaneous thrust, but the associated

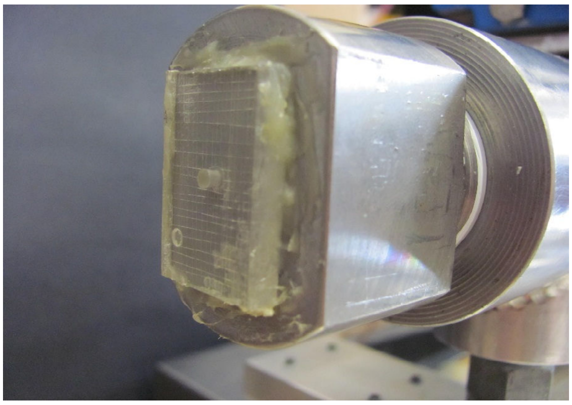
Fig. 2. Supersonic thruster unit

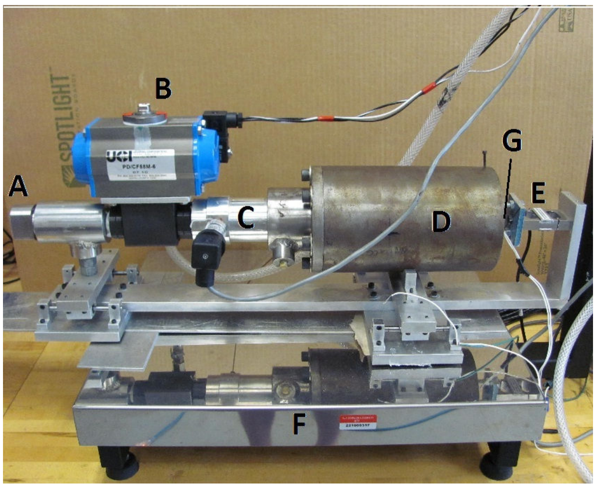

Fig. 3. Thrust Test Apparatus. (A) Supersonic nozzle; (B) Pneumatic valve; (C) Pressure transducer; (D) Pressure vessel; (E) Thrust load cell; (F) Digital load platform; (G) Electric plug heater

mass flow rate was estimated by assuming that the density of the fluid remaining in the pressure tank was equal to the density of carbon dioxide corresponding to the measured instantaneous temperature and pressure. Pressure sensor response errors could be neglected on the basis of the nearly negligible influence of very small relative pressure changes on the thermodynamic properties. That was not the case for the measured temperatures. The sheathed Type T thermocouple was immersed on the centerline axis of the slow-moving, supercritical fluid, as it flowed toward the nozzle and the varying convective heat transfer coefficient was both difficult to estimate and did not facilitate rapid thermal response. This same response problem was observed by Mignot *et al* [3,4]. Hence, it was concluded that the measured time-varying temperature could not be used as the instantaneous carbon dioxide stagnation temperature and direct measurement of the instantaneous total mass was required to estimate the instantaneous propellant mass flow rate. The test stand was modified so that the entire test rig could be mounted atop a Torbal BA150E platform scale. The platform scale provided instantaneous digital mass measurements with a precision of ± 0.02 kg. Since the center of mass of the test apparatus shifted slightly as the carbon dioxide was ejected, and the varying torque produced by the operating nozzle could also influence the instantaneous mass measurement, the platform scale digital output corresponding to a given instantaneous mass needed to be examined. Using a set of precision weights, the scale output was recorded when the empty test apparatus was mounted on the scale platform while no nozzle thrust was simulated and those tests were repeated when a constant nozzle thrust of 65 N was simulated using a tension line and monitoring the applied tension with the thrust load cell. The digital output recorded during simulated thrust conditions did not produce a significant error in the measured mass, based on the ±0.02 kg output precision.

The test apparatus consisted of a nominal 0.001 m^3 cylindrical steel pressure vessel (with a maximum design pressure of 400 bar) mounted horizontally on the sliding rail support structure. An Omega LC101-50 stainless steel S Beam load cell with an output precision of ± 0.067 N was mounted flush to the end of the pressure tank to measure the thrust produced during blow-down. An Omega PX4204-6KG5V pressure transducer, accurate to within 1 atm, mounted opposite to the thermocouple was used to measure instantaneous fluid pressure. After the pressure vessel was charged with dry ice, an end-mounted electric heater was activated and the time-varying carbon dioxide temperature and pressure were monitored. When the desired temperature and pressure test point was reached, a UCI 3/4-inch NPT pneumatically actuated ball valve was activated to initiate the nozzle flow. The ball valve could go from fully closed to fully open in 0.6 seconds. The CO_2 flowed subsequently through a Mach 2 supersonic nozzle [1] with a 2 mm diameter throat, and was released to the atmosphere. A Labview program utilizing a National Instruments USB-6210 data acquisition card was employed to measure instantaneous thrust, total mass, carbon dioxide temperature and pressure at 1,000 samples per second.

3. TEST PROCEDURE

In some respects, the test procedure simulated a Mars surface operation. On the Martian surface, a thermoelectric cooler would be utilized to condense carbon dioxide out of the atmosphere and the resulting solid would be transferred to a closed container. Subsequently, the thermoelectric cooler would be operated as a heat pump to heat the constant volume container above the critical temperature, producing the supercritical propellant. Rather than using a thermoelectric heat pump in a simulated Mars environment, commercial dry ice was added to the pressure vessel and the tank was heated using an electric plug heater. Disk-shaped chunks of dry ice with the same nominal diameter as the inside diameter of the pressure vessel were cut from commercial dry ice blocks and weighed with a calibrated spring scale, to achieve a specified initial carbon dioxide mass. The density of commercial dry ice varied somewhat, but initial densities on the order of 1,000 kg/m^3 could be readily achieved.

The critical temperature and pressure of carbon dioxide are 31.03 °C, 73.8 bar, respectively. From the standpoint of producing a usable pressurized propellant, the temperature isotherms for carbon dioxide, shown in Figure 4 were an important consideration. While the fluid was not pure carbon di-

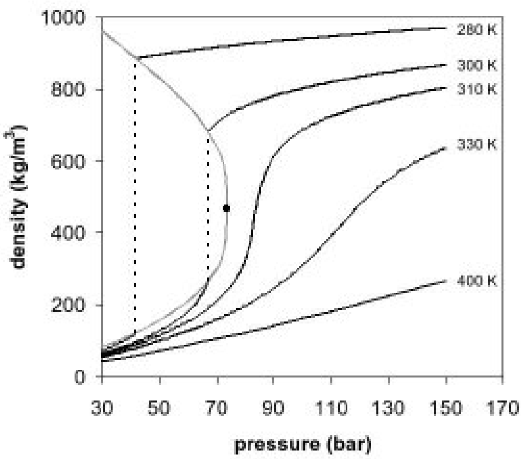

Fig. 4. Carbon Dioxide Pressure-Density Isotherms

oxide, the figure shows that very high initial pressures can be achieved at moderate temperatures if the initial density is above 500 kg/m^3.

The pneumatic valve used to initiate the blow-down tests was open initially, in order to prevent pressurization of the tank while the flanged end cap was bolted and sealed after the dry ice charge was inserted. Since the pressure vessel and associated hardware were at room temperature at the beginning of the charging procedure, some CO_2 sublimated and escaped prior to sealing the end cap and closing the pneumatic valve. It was necessary to increase the initial carbon dioxide charge mass by an amount corresponding to the estimated dry ice loss that was expected to occur during the charging and sealing process. As a result, the initial mass of carbon dioxide only approximated the desired initial conditions. As soon as the pressure vessel was sealed and the pneumatic valve was closed, the electric heater was activated and the system was heated to the desired nominal temperature and pressure conditions.

4. RESULTS AND DISCUSSION

Supersonic nozzle performance will be affected by the particular blow-down process. Consequently, it was desirable to characterize thrust performance when the expected blow-down process produced a superheated vapor (Region 1, in Fig. 1); a condensing two-phase mixture (Region 2); and a vaporizing two-phase mixture (Region 3). To that end, supercritical CO_2 blow-down experiments were devised to explore all three regions. The blow-down test starting at 45 °C, 9.24 MPa, was expected to represent Region 2 and those data will be plotted as yellow lines in the graphs that follow. The blow-down test that started at 61 °C, 22.3 MPa was expected to represent Region 3 and those data are plotted as blue lines; and the blow-down test that started at 74 °C, 10.7 MPa, was expected to represent Region 1, plotted as green lines.

Since the temperature of the exiting carbon dioxide gas is quite low, carbon dioxide and water condensate permit flow visualization. A representative under-expanded supersonic blow-down flow is shown in Figure 5, and an over-expanded supersonic flow, exhibiting the classical shock pattern is shown for a later stage in the blow-down test in Figure 6. Using digital motion picture records of the flow pattern, it was possible to determine the exit phase flow conditions corresponding to the measured thrust and pressure. The visual data supported the descriptive T-s process regions (Fig. 1) identified by Mignot *et al* [4].

Measured thrust as a function of time for the three blow-down tests is shown in Figure 7. While not readily apparent in that figure, the pneumatic valve was observed to open so rapidly for the lower-pressure (Regions 1 and 2) blow-down tests (~0.01 sec. vs ~0.06 sec.) that the test rig (A,B,C,D,G in Fig. 3) “hammered” the load cell during blow-down initiation, exciting a load cell oscillation. The oscillation was damped and has been smoothed in the processed data.

The data in Fig. 7 show that phase-change processes (associated with Regions 2 and 3) result in higher measured thrust levels for extended periods of time.

In agreement with the observations of Mignot *et al* [3,4], the sheathed thermocouple (mounted opposite pressure transducer “C”, shown in Fig. 3) did not respond rapidly to changes in the carbon dioxide fluid temperature. Hence, it was not possible to use the measured instantaneous pressure and temperature to determine the density of the mass of carbon dioxide remaining in the pressure vessel and the measured instantaneous total mass was employed. Because of noise, it was necessary to employ moving averages to smooth the mass vs time data for the Region 3 blow-down test, shown in Fig. 8, is representative.

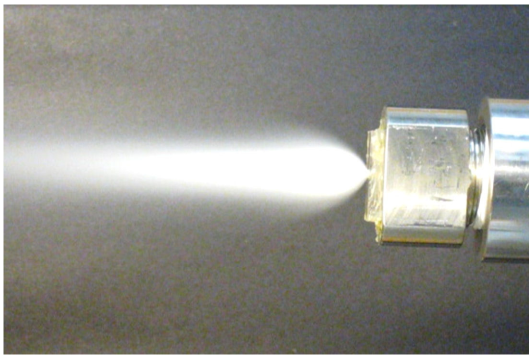

Fig. 5. Typical under-expanded, early blow-down jet flow

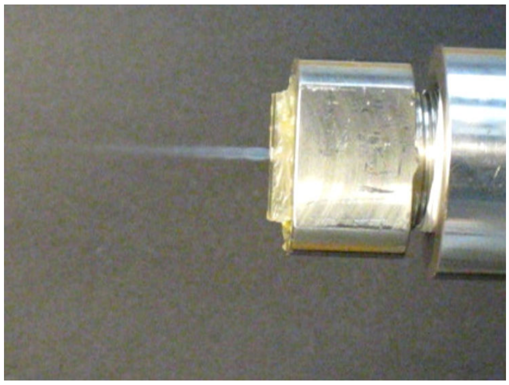

Fig. 6. Typical over-expanded, late-stage blow-down jet flow

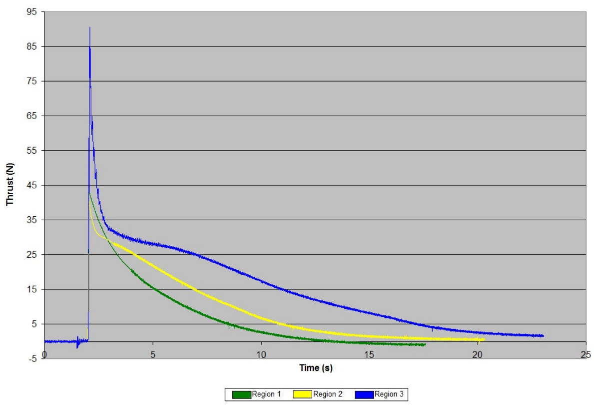

Fig. 7. Measure thrust vs time during blow-down

The data scatter associated with instantaneous total mass presented problems in determining the instantaneous mass flow rate. Since it can be expected that the mass flow rate as a function of time is a relatively smooth curve, the objective was to estimate instantaneous mass using a moving average, exploiting the 1000 samples/second data rate. The total mass data were first averaged using a 1500 point moving average and that resulting history was averaged again using a 2000 point moving average. Subsequently, the instantaneous mass flow rate was calculated using a centered finite difference formula, and the resulting mass flow rates as functions of time for the three blow-down tests are shown in Figure 9.

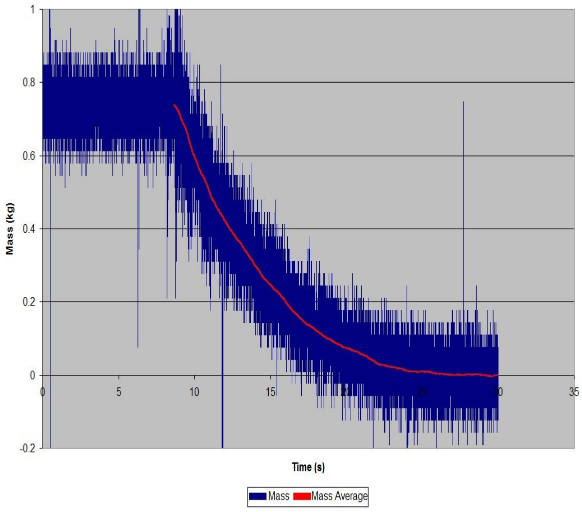

Fig. 8. Representative total mass vs time (Region 3, test)

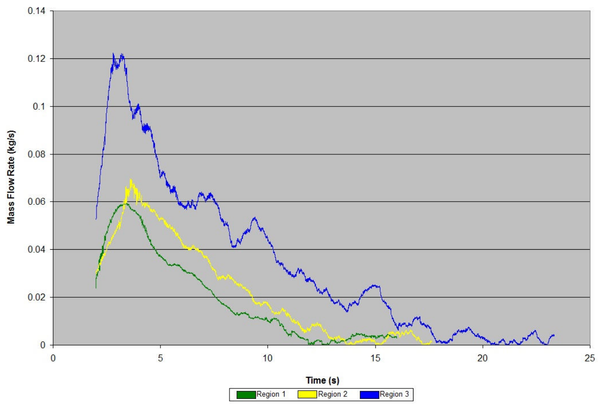

Fig. 9. Mass flow rate as a function of time.

As can be seen in Figure 9, there is considerable scatter in the processed mass flow rate data. In addition, the initial mass flow rates are suspect because of start-up transients.

4.1 Specific Impulse Calculations

Specific impulse, I_{sp}, is defined:

$$I_{sp} \equiv \frac{T}{\dot{m}g}, \tag{1}$$

where T is the measured thrust in Newtons, $\dot{m}$ is the measured propellant mass flow rate in kg/s, and g is the gravitational constant (9.8066 m/s^2). The specific impulse of supercritical carbon dioxide propellant expanded through a Mach 2 nozzle, when starting from the three blow-down regions can be calculated using Eq. 1. However, we have already pointed out that the initial mass flow rates are likely too low as a result of start-up transients. Furthermore, Fig. 9 shows that the variation in the mass flow rates, calculated employing numerical differences of averages, become sufficiently erratic after about ten seconds, on a percentage basis, that smooth curves were fared through the mass flow rate plots beyond 10 seconds (not shown) in order to reasonably estimate specific impulse. With those restrictions and limitations in mind, specific impulse as a function of time for the three types of blow-down processes are shown in Fig. 10. It can be seen from

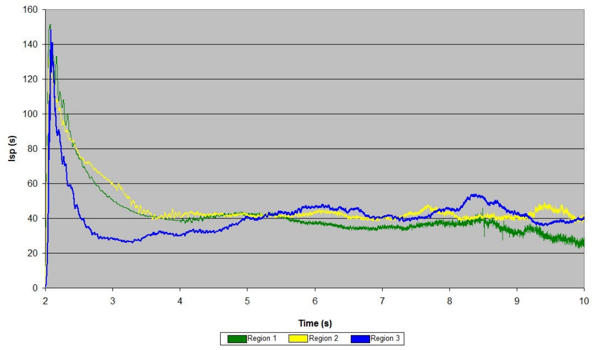

Fig. 10. Variation of specific impulse with time for three types of blow-down process

this plot that supercritical carbon dioxide can be expanded through a supersonic nozzle to produce an initial specific impulse that is on the order of 100 seconds for the first few seconds, with a sustained specific impulse of approximately 40 seconds, for approximately 30 seconds (the last 20 seconds are not shown in the figure) when expansion occurs from either Region 2 or Region 3.

5. CONCLUSIONS

Based on blow-down tests of supercritical carbon dioxide expanding through a Mach 2 nozzle, it is possible to produce 100 s, specific impulse spikes for a few seconds using indigenous carbon dioxide. That type of spike could sustain high-thrust bursts to propel a penetrator into a surface or to extract a trapped object. Relatively low (40 s) specific impulse propellant performance can be sustained, possibly for minutes at a time, by freezing then heating indigenous carbon dioxide.

When the blow-down process was initiated from a thermodynamic state that produced a superheated vapour expansion process, overall performance was low and thrust was sustained over much shorter time intervals. When the blow-down process was initiated from a thermodynamic state that produced a vaporizing two-phase expansion process, thrust duration was extended but overall specific impulse levels were reduced during the initial high-thrust time interval. The best overall performance was achieved when blow-down was initiated from a thermodynamic state where the blow-down process was characterized as a condensing two-phase process.

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