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José N. Hinckel
INPE - Instituto Nacional de Pesquisas Espaciais
São José dos Campos - SP - Brazil

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DEVELOPMENT OF A 115 NEWTON THRUST HYDRAZINE CATALYTIC THRUSTER

José N. Hinckel*
Instituto Nacional de Pesquisas Espaciais
Caixa Postal 515
12201-970 – São José dos Campos, SP – Brazil

Abstract

This paper describes the design, fabrication and testing of a hydrazine catalytic thruster with a vacuum thrust of 115 newton. The design guidelines and procedures are presented and discussed. The thruster was tested over the range of feed pressure commonly used in blowdown systems with a ratio of 4:1; from 22 bar to 5.5 bar. The tests were conducted in atmospheric and altitude conditions. The measured thrust, chamber pressure and specific impulse were in good agreement with the design value. The mechanism responsible for the low frequency chamber pressure oscillations, observed during some test runs, is discussed.

Introduction

Hydrazine catalytic thrusters are the most popular choice of mass ejection reaction mechanism for attitude and orbit control systems for satellites. Hydrazine monopropellant thrusters are also used for roll control of many of the Launch Vehicles in use today.

The widespread use of hydrazine catalytic thrusters for control systems is due to the inherent reliability and other characteristics such as:

Restartability. Since there is no need for ignition mechanisms, the thruster can be restarted an almost unlimited number of times.

Throttling. By operating the thruster in pulsed mode with different duty-cycles, the time-averaged thrust can simulate throttling in a wide range, with no need for complicated injection head, and mechanisms for feed pressure control. Also since it can be fed from a blowdown tank pressurization system, there is no need for a high pressure gas tank and a pressure regulators.

Simplicity. Operation of the thruster is accomplished by the opening of a valve, with no need for a start sequence and checks to verify ignition and proper operation of several valves and controls.

Besides hydrazine catalytic thrusters, reaction control systems can also use cold gas thrusters, bipropellant thrusters and ion thrusters. Cold gas thrusters are used when the total impulse required is very small, the thrust level is low or when the other high energy systems would present hazards to nearby equipment or humans.

Bipropellant systems are used when the total impulse required is high, the minimum impulse bit is relatively high and the total number of pulses is not very large. Although the specific impulse of the bipropellant system is higher than the hydrazine monopropellant, for small and medium impulse systems, this advantage is offset by the added weight of duplicate tanks, feed lines, valves and fixtures.

Design and Fabrication

The design procedures followed were based on empirical correlations described in [1], and experimental data obtained from previous tests of a 2 newton thruster developed at INPE. Fabrication of the thruster, except the catalyst, was done by COPESP (Coordination for Special Projects).

The areas of the injection orifices, nozzle throat and injection capillary tubes were calculated to satisfy the thrust level at the beginning of life of the system (i.e. with the tank at maximum pressure), and to satisfy the condition that at the end of life of the system, the pressure drop in the injection orifices be greater than 10% of the catalytic chamber pressure.

The weight of the thruster assembly was approximately 0,75 kg. Replacing the flanged joints by welded joints, and reducing wall thickness should reduce the weight to less than 0.5 kg.

The thruster valve

The valve has a single seal with a PTFE insert poppet and a metal seat. The spring loaded poppet moves in axial direction, with a travel path of 0.65 mm. The valve was fabricated in AISI-304 and AISI-430 stainless steel. The valve is electrically operated from a 28 V dc power supply. Opening and closing time are approximately 15 milliseconds. The orifice diameter is 3 mm.

The injector head

The injector head is comprised of a trim orifice, seven capillary tubes, each one with five injection orifices,

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*Research Scientist, Member AIAA

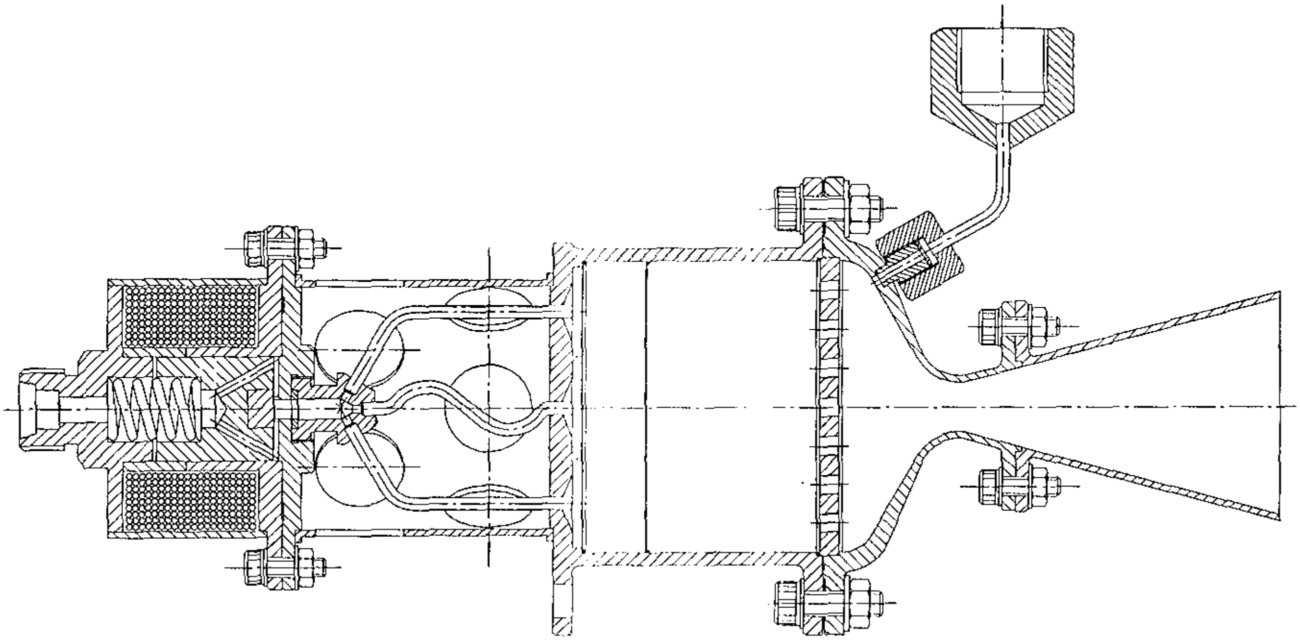

Figure 1: Schematic drawing of thruster

and the injector face. The capillary tubes are brazed to the valve exit flange and the injector face. The tubes have a diameter of 2 mm and are made of Inconel 600. The orifices have a diameter of 0.3 mm and were drilled symmetrically around the circumference of the tube with a laser welder-cutter. The orifices are located at a distance of 0.5 mm from the injector face. The hydrazine is injected perpendicular to the chamber axis.

The injector face has seven small cylindrical chambers 2 mm deep, with a slightly conical head where the injector capillary tubes inject the hydrazine. As the hydrazine is injected into the chamber, it splashes against the conical part of the chamber. A fine mesh size screen separates these small chambers from the main catalytic chamber.

The pressure drop of each capillary injector is set to a value slightly higher than the design value. After assembly of all injector capillaries with the valve and injector face, the total pressure drop of the combined system is adjusted to design value in a trim orifice, located at the valve exit flange.

The catalytic chamber

The catalytic chamber is divided in two parts. The upstream part is filled with a layer of fine mesh catalyst, and the downstream part is filled with a layer of coarse catalyst pellets. The two layers are separated by a platinum-rhodium screen. The screen or its support ring must be welded to the chamber wall to prevent the fine catalyst from being carried into the large voids of the coarse catalyst, creating a large flow resistance and leaving empty space near the injector head.

The catalyst for both layers was fabricated at the Laboratório de Combustão e Propulsão of the INPE unit at Cachoeira Paulista. The fine mesh catalyst is of the granular type with mean diameter between 0.6 and 0.8 mm. The coarse catalyst is in the form of extruded pellets with a diameter of 3 mm and lengths varying from 1 to 3 mm.

The catalytic chamber and the injector face were machined in Inconel 600 in a single piece.

The diameter of the chamber and the length of the fine and coarse catalyst layers were calculated to satisfy conditions of chamber bed load and pressure drop. The length of the first layer was 7 mm. The length of the coarse catalyst layer was 30 mm. Reference [1] presents results of extensive testings with Shell 405 catalyst, and establishes ranges for these parameters. The recommended ranges for the chamber bed loading and pressure drop are 1–5 $g/cm^2/s$ and 1.5–2 bar respectively.

Since the specific area and mesh size of the catalyst fabricated at INPE are very close to the same parameters rated for the Shell 405 catalyst, the empirical correlations established in [1], for chamber pressure drop and ammonia decomposition, these were used for the calculations of the chamber diameter and length of catalyst layers.

The chamber bed load at beginning of life was fixed at 3.5 $g/cm^2/s$ resulting in a chamber diameter of

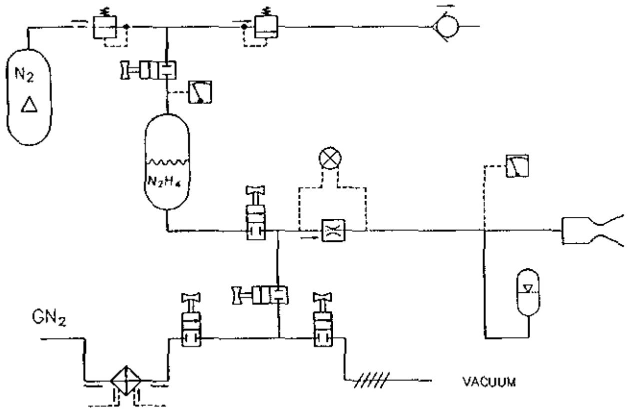

Figure 2: Schematic representation of the feed line

45.7 mm.

For a thruster with a long life, long accumulated operating time, and a large number of starts, the chamber bed load should be low, to avoid performance degradation due to catalyst breakup.

Thrusters designed for short life, will in general, have a higher bed load, using less catalyst, saving weight and having a smaller envelope.

A Platinum-Rhodium screen, supported by a perforated plate, maintained the catalyst tightly packed, and prevented it from being washed away by the gas flow.

The thrust nozzle

The thrust nozzle was fabricated in two parts. For atmospheric tests, a nozzle with an exit area ratio of 5.3:1 was used. A nozzle extension with an exit area ratio of 40:1 was used for tests in the vacuum chamber. The converging section has a 60° semi-angle. The diverging section is conical with a 15° semi-angle.

Two circular arcs join the converging and diverging sections. The upstream arc has a radius of 7.6 mm and the downstream arc has radius of 1.9 mm. The throat diameter is 7.6 mm.

The Test Facility

Most tests were conducted at atmospheric conditions, since no altitude test chamber is available at INPE for thruster delivering more than 5 newton of thrust in continuous mode.

A schematic representation of the hydrazine feed and pressurization line is shown in Fig. 2. The tank was pressurized with GN_2. No membrane was used to separate pressuring gas from the hydrazine fuel. Pressurizing nitrogen gas can therefore be absorbed by the hydrazine fuel, especially when it remains under high pressure for long periods of time.

Mass flow rate was computed from the measurement of the pressure drop across an orifice in the main feed line. The pressure drop was measured with a wet/wet Druck differential pressure transducer. The maximum base pressure for the transducer is 30 bar and the differential pressure range is 2 bar. The orifice was designed for the optimal response range of the differential pressure transducer.

The feedline was built with 6 mm stainless steel tubes.

Before filling the feedline with hydrazine, it was flushed with hot nitrogen. The nitrogen gas was exhausted through the thruster while the chamber was also being heated. It is very important that the catalyst be dried before the test, to avoid breakup as it is heated up to over 900° C during thruster firing.

To dampen the strong water hammer due to the closing of the valve, a hydraulic damper was installed at the entrance of the thruster valve. The damper consists of a small chamber with a small volume of gaseous nitrogen which is in direct contact with the hydrazine. Without the hydraulic damper a water hammer of up to 100 bar propagates in the line when the thruster valve is closed.

To avoid the formation of a highly explosive hydrogen/air mixture in the vicinity of the thruster a powerful blower was mounted at the exit of the thruster exhaust. In this way the hydrogen was rapidly mixed to a concentration below the explosive level.

The thruster was attached directly to the load cell, so that the thrust force was applied onto the cell. The thruster was mounted in the vertical position with the gases being ejected upward.

The test program

Two series of tests were conducted with the thruster. In the first series of tests the catalyst was loaded according to the design described above (i.e. a fine mesh screen was mounted flush with the injector face, leaving a small empty cavity in the region of each injector tube end). In this case, the injected hydrazine would first splash against the injector face, deflecting towards the screen and then hitting the fine catalyst layer.

In the second series of tests, the injector face screen was removed, so that the hydrazine was injected directly onto the fine grain catalyst. In this case the small cavity at each injector tube end, was filled with catalyst.

In each series, the thruster was tested at different pressure levels, varying from 5.5 bar to 22 bar. For each pressure level, the thruster was fired in continuous mode and pulsed mode. The continuous mode shots had a duration of 30 seconds. The pulsed mode shots consisted of pulse trains with 30 pulses. Duty-cycles of 10%, 20% and 50% were tested for each pressure level.

The second series of tests included firing shots in the altitude vacuum chamber. Due to limitations in the vacuum pumping capacity, the longest duration continuous shot was 5 seconds.

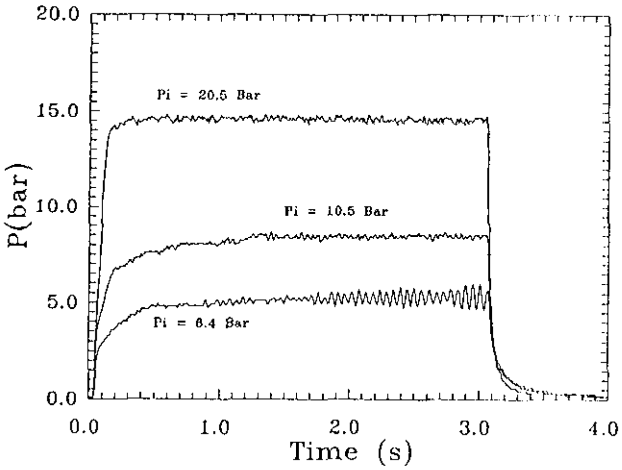

Figure 3: Chamber pressure trace for different feed pressure

All tests were conducted with the catalytic chamber pre-heated to a temperature of 100° C.

The test results

The test results obtained with the two configurations were markedly different. Large chamber pressure oscillations were observed in the first series of test, with the empty chambers at the injector face.

These chamber pressure oscillations were observed for the entire range of feed pressure tested. In the low feed pressure range, the amplitude of the pressure oscillations was 50% of the chamber pressure, and the frequency was approximately 20 Hz. As the feed pressure increased, the amplitude of the pressure oscillations decreased and the frequency of the oscillations increased. For a feed pressure of 20 bar, the peak to peak magnitude of the pressure oscillations was approximately 30% of the mean chamber pressure and the frequency of the oscillations was approximately 35 Hz.

In the second series of tests, very smooth pressure trace was observed, except for the very low feed pressure range. For feed pressure higher than 10 bar the peak to peak amplitude of the pressure oscillations was less than 5% the value of the mean chamber pressure.

No significant difference was observed in the chamber pressure for tests conducted at atmospheric pressure and in the vacuum chamber.

The pressure trace for three feed pressure levels is shown in Fig. 3. These traces are from tests conducted in the vacuum chamber. For these tests, the chamber pressure before start of the thruster was 10^{-3} mbar. At the end of the test the chamber pressure was approximately 10 mbar.

The measured thrust from the atmospheric and vacuum test are shown in Fig. 4. The nominal design value is also shown.

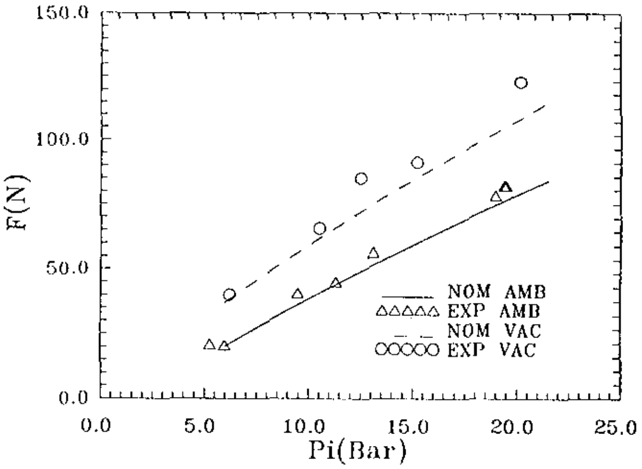

Figure 4: Design and measured thrust

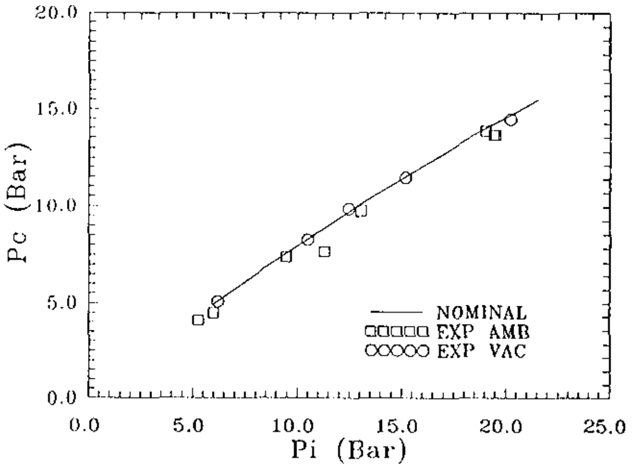

Figure 5: Design and measured chamber pressure

For the atmospheric tests, the short nozzle with an area ratio of 5.3:1 was used. A nozzle extension with area ratio of 40:1 was used for the vacuum tests.

The results of chamber pressure measurements and calculated thrust coefficients for these tests are shown in Figures 5 and 6. For low chamber pressure, the thrust coefficient departs considerably from the nominal value. This occurs because of the flow separation due to overexpansion, since the 5.3 nozzle area ratio is optimal for chamber pressure of 15 bar.

A model for the chamber pressure oscillations

As described above the thruster was tested with two different loads of catalyst, one with a small empty chamber in the injection region, and one where the injector tube end penetrated the fine mesh catalyst layer. Large pressure oscillations were observed in the first

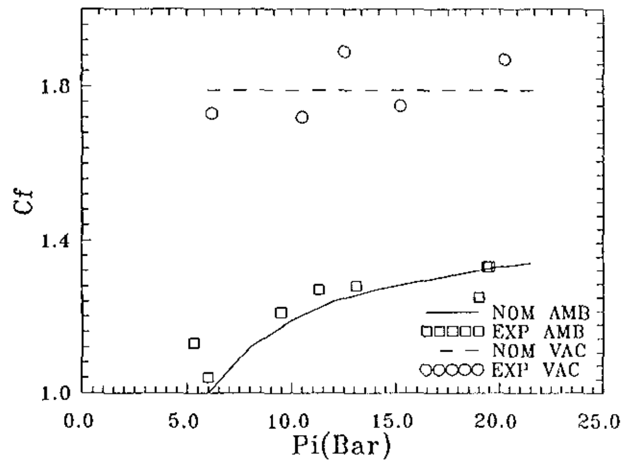

Figure 6: Design and measured thrust coefficient

configurations, while a very smooth pressure trace was obtained with the penetrating injector tube.

The main mechanism for the pressure oscillations is the high bed load in the vicinity of the injection point. Since there are five injection orifices in a very small volume, the local bed load is very high. The small empty chamber is rapidly filled with liquid hydrazine and the splashing of the injected hydrazine onto the injector face, and fine atomization, does not occur.

We have therefore a liquid hydrazine "drop" growing rapidly, from the catalyst free cavity, at the end of the injection tube. As the drop expands into the catalyst layer, the contact surface between the hydrazine and the catalyst increase accelerating the decomposition reaction of the hydrazine. This faster reaction in turn increases the rate of gas generation and therefore the chamber pressure rises.

As a result of the faster reaction we have therefore more energy available for the evaporation of the hydrazine drop, and, due to the increased chamber pressure, a higher heat transfer coefficient between the hot gases and the hydrazine drop. Since the higher chamber pressure will also result in the decrease of the injected hydrazine flow, and an increased rate of hydrazine evaporation, the volume of the liquid drop starts to shrink and is rapidly consumed. As the hydrazine drop is consumed the hydrazine supply is reduced and the chamber pressure decreases. The process then starts anew.

A simplified calculation shows that for the frequencies of the chamber pressure oscillations observed, the maximum volume of the liquid drop of hydrazine accumulated near the injection orifice would be somewhat bigger than the volume of the catalyst free chambers at each injection tube.

The qualitative behavior of the magnitude and frequency of the pressure oscillations are also in agreement with the expected behavior from the model described.

As the feed pressure increases, the rate of growth of the liquid drop also increases, and since the chamber pressure is higher, the rate of shrinking of the liquid drop when the chamber pressure starts to rise, is also faster. The frequency of the oscillations is therefore higher.

At higher pressure, the injector pressure drop and chamber pressure drop are higher, so that the coupling between the chamber pressure and the feed system is weaker. This has a damping effect on the the pressure oscillations.

With the second catalyst load, the hydrazine being injected directly onto the catalyst is rapidly atomized and evaporated. Contact with the catalyst is better, and decomposition reaction is faster so that liquid hydrazine does not accumulate in the injection region.

Conclusion

A hydrazine thruster with vacuum thrust of 115 newton was built and tested. A model for low frequency chamber pressure oscillations is proposed, and the implications of this model are compared with results obtained from the tests.

Further tests should be conducted to verify the model. An analytical formulation of the mechanisms of the chamber oscillations would also serve as a useful tool to verify the validity of the proposed model.

High local chamber bed load can lead to chamber pressure oscillations associated with accumulation of liquid hydrazine in the chamber, and interaction with feed system. To avoid accumulations of liquid hydrazine in the catalytic chamber, we must therefore make sure that, the amount of energy released near the injection point is high, and that the heat transfer between the hot gases and the liquid hydrazine drops is fast enough to ensure rapid evaporation of the injected stream.

References

[1] Rocket Research Corporation, Development of Design and Scaling Criteria for Monopropellant Hydrazine Reactors employing Shell 405 Spontaneous Catalyst. Seattle. Washington, 1965. (NASA-CR-82456).

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