REVIEW OF PLASMA PROPULSION ACTIVITIES IN ITALY

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Abstract

This paper reviews the progress and results of plasma thruster technology development in Italy since the last International Electric Propulsion Conference. This work includes low power (1 kW-class) and moderate power (10-15 kW) arcjet technology development at BPD Difesa e Spazio, low power arcjet and gas-fed MPD thruster research at Centrospazio and solid Teflon propellant MPD thruster research at the University of Rome. The two arcjet test facilities at BPD are now operational. Parametric performance mapping is being conducted on low power and moderate power arcjets. A laboratory model low power arcjet has demonstrated a specific impulse of 440 s using simulated hydrazine while initial testing of a laboratory model moderate power arcjet has demonstrated over 650 s. Two similar water-cooled engines showed the same performance on hydrogen over a specific impulse range of 500 to 620 s. Preliminary estimates of gas-fed ring anode MPD engine performance correspond to a specific impulse range of 1000 to 3000 s with efficiencies in the range of 15 to 30%. Breach-fed and radially-fed solid Teflon MPD thrusters were tested over an instantaneous power range of 0.6 to 3 MW. Future plans include engineering model arcjet development, MPD thruster testing, detailed arcjet flight system definition, arcjet breadboard PCU testing and detailed definition of the DIVA experiment.

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INTRODUCTION

Research activities in plasma propulsion began in Italy in the early 1980s with system definition studies on MPD thruster systems for orbit raising of large spacecraft. Additional studies were conducted to examine solid Teflon MPD thrusters for North-South station keeping (NSSK) missions. These system studies were followed by experimental development activities on gas- and Teflon-fed MPD thrusters. In 1987 the program focus was expanded to include arcjet propulsion system technology development. Investigations of two classes of arcjet thrusters began, low power arcjets (1 kW-Class) for NSSK and moderate power arcjets (10-15 kW-class) for orbit change of large man-tended space platforms. European applications for arcjets are foreseen in the middle to late 90’s.

This paper will review the activities performed in Italy in plasma propulsion since the last International Electric Propulsion Conference and summarize the status of the ongoing activities. This work includes low power (1 kW-class) and moderate power (10-15 kW) arcjet technology development at BPD Difesa e Spazio (BPD), low power arcjet and gas fed MPD thruster research at Centrospazio (CS) and solid Teflon propellant MPD thruster research at the University of Rome (UoR). The activities which are discussed include facilities status, low power arcjet system technology development activities, 10 kW/N arcjet engine testing progress, optical plume analysis results and gas-fed and solid teflon-fed MPD thruster testing. The status of the systems studies activities on low power arcjet system definition and the DIVA experiment are also discussed.

ARCJET TECHNOLOGY DEVELOPMENT

Two classes of arcjets are being investigated in Italy by BPD and its subcontractors. Low power arcjet (0.5 - 1.5 kW) technology development is being conducted with support from CS while 1 N-class arcjet (10 - 15 kW) technology development is being conducted by BPD and has been supported by the University of Stuttgart (IRS). The recent test results from these programs are summarized below. The facilities used at BPD and CS to conduct arcjet technology development are also summarized below.

Facilities and Diagnostics

BPD has two operational arcjet test facilities and CS has one facility operational.

BPD Difesa e Spazio

BPD has installed two state-of-the-art arcjet test facilities designated VP-1 (for testing of both classes of engine and tests with hydrazine) and VP-2 (for low power arcjet development), see Fig. 1. Detailed descriptions of these facilities can be found in References 7, 14, 15 and 18. Both facilities are operational. Each facility has fully independent vacuum pumping systems, power supplies, data acquisition and control systems and diagnostics. Both facilities share the laboratory cooling water system and the nitrogen and hydrogen gas supplies. Both pumping groups can be used to pump on the VP-1 vacuum chamber providing an increased pumping speed by opening butterfly valve CV and closing the AV butterfly valve.

Facility VP-1 (Fig. 2), is composed of a water-cooled vacuum chamber 1.6 m in diameter and 4.0 m long connected to a four-stage pumping group. The first stage of the pumping group is composed of two 25,000 m³/h and one 18,000 m³/h Roots pumps connected in parallel. The second stage is composed of a single 12,000 m³/h Roots pump followed by the third stage 2,000 m³/h Roots pump and the fourth stage 500 m³/h rotary pump, see Fig. 3. The system pumping speed is 58,000 m³/h at 0.01 mbar. The facility provides a background pressure of 0.02 mbar during moderate power engine operation at a simulated hydrazine mass flow rate of 150 mg/s.

The auxiliary systems on VP-1 include the propellant feed system (PFS), power supply, data acquisition and control system (DACS), cooling water system, diagnostics and safety as shown in Fig. 3. The PFS can provide argon, nitrogen, helium, hydrogen and ammonia
to the engine alone or in mixtures and is designed for endurance testing. The flow rates can be varied between 1 and 300 mg/s for each gas or mixture of gases. A separate hydrazine propellant feed system can provide between 12.5 and 250 mg/s of hydrazine. An exhaust gas neutralization system has been installed to neutralize ammonia (NaClO/water) and hydrazine (NaOH/water). A vacuum chamber cooling water system can continuously remove up to 100 kW. The power supply consists of start-up and run units and can be operated continuously at 100 kW. A programmable logic controller (PLC) is used for facility control and safety functions. A continuous 10 kW battery power supply and 50 kW motor/generator set provide power to the PLC and fourth stage pump to maintain the facility in a safe condition in case of a power failure and enable the PLC to shut down the systems in the proper order. Diagnostics facilities include a thrust balance (0.05 to 1.5 N), mass flow meters, temperature probes (pyrometer and thermocouples), current and voltage transducers and various facility pressure transducers which are monitored by a DACS-based on a personal computer which includes 24 input channels at 100 kHz for one channel. In addition, the diagnostics facilities include an emission spectroscopy system (for arcjet plume velocity profiles, species concentrations, atom temperature and/or electron density) and various pressure, temperature and camera outputs.

Facility VP-2 is composed of a vacuum chamber 0.8 m in diameter and 1.6 m long connected to a four-stage pumping group, see Fig. 3. The first stage consists of two 13,000 m³/h Roots pumps connected in parallel. The second and third stages are made up of 9,000 and 2,400 m³/h Roots pumps, respectively, while the fourth stage consists of a 450 m³/h rotary pump. The system pumping speed is 19,000 m³/h at 0.03 mbar. A first stage bypass is included for reduced pumping speeds.

The auxiliary systems on facility VP-2 include an independent power supply system, DACS and diagnostics allowing parallel testing in both facilities. The PFS can feed nitrogen, hydrogen, ammonia vapor and mixtures of these gases to the engine over a flow rate range of 1 to 100 mg/s for each gas. A cooling water system provides cooling for the vacuum chamber end caps and test stand. The power supply is capable of starting and operating low power arcjets of up to 2.5 kW. A personal computer based DACS is used in the facility (16 channels, up to 500 KHz per channel). Diagnostics facilities instrumentation enables the measurement of thrust, various pressures and temperatures, and engine operating voltage and current. The emergency power system (10 KW continuous battery and 50 KW motor/generator set) is also connected to facility VP-2.

Centrospazio

Centrospazio uses the IV3 facility for low power arcjet testing.10,11 The IV3 facility consists of a steel vacuum chamber connected through a gate valve assembly to the pumping system, see Fig. 4. The vacuum chamber is made up of two sections; a cylindrical test section with removable end caps, 1.25 m in diameter and 1.75 m in length, and a 1.25 m diameter manifold tube connecting the tank test section to the gate valve assembly. A 0.7 m-diameter flange on the side of the test cell opposite the pump access manifold tube has been mounted on a trolley and supports the main instrumentation flanges (an observation window and twelve feedthroughs). The pumping system consists of two oil booster pumps backed by four rotary pumps with a total pumping speed of 20,000 l/s at a background pressure of 10⁻³ mbar. Two 24" gate valves are used to isolate the pumping system from the vacuum chamber and facilitate modification of the experimental set-up during the course of a test run.

The auxiliary systems include a PFS, power supply and DACS. The PFS was designed to provide argon, nitrogen, hydrogen or mixtures of these gases (to simulate ammonia or hydrazine) to the arcjet at flow rates between 0 and 60 mg/s. The flow rate was measured with a precision of 0.1% of FS. Each gas was filtered by a Messer-Grisham Oxisorb to ensure an oxygen free propellant supply to the arcjet. The power supply unit consists of a start-up circuit and a run power supply. The start circuit provides a 2.0 kW pulse across the electrodes for 20 μs and the run power supply can provide up to 70 A and has an open circuit voltage of 150 V. A dedicated DACS equipped with a high speed voltmeter and a 24 channel FET multiplexer was implemented to record analog measurements. The DAS was connected to a workstation for data recording and initial processing. The thrust stand used for the arcjet tests consisted of three basic elements: a single degree of freedom suspension for the thruster, a load cell and a remotely-operable calibration system.

Low Power Arcjets

Testing of low power arcjets is presently under way at both BPD and CS. The testing activities at CS are focused on engine modelling.14 PCU design.15 Operating envelope definition and parametric performance mapping using nitrogen, hydrogen and mixtures of these gases.12,13,19,20 The test activities at BPD include parametric performance mapping using nitrogen, hydrogen, ammonia and mixtures of these gases12,13,18,20 but will be centered toward testing on catalytically decomposed hydrazine and endurance testing.
Figure 5 shows the low power arcjets being investigated. The MOD-A engine is presently under test in both laboratories for accelerated development and data cross checking. This laboratory model engine has been designed to enable simple changeout of the anode, cathode and gas injection piece for parametric testing without disassembly of the entire engine. Typical data for the MOD-A engine using a gas mixture to simulate hydrazine is shown in Fig. 6. The specific impulse-specific power (power divided by the mass flow rate) characteristic is shown for a flow rate range of 40 to 50 mg/s.

The MOD-B engine has also been designed for simple changeout of the anode, cathode and injector plate along with providing a design which can be used for both 'cold' gaseous propellants and decomposed hydrazine. Thermal analysis was conducted on the MOD-B design. The grid used for thermal analysis along with the initial results are shown in Fig. 7. A nozzle outer surface temperature of 1250 °C is expected during engine operation. Figures 8 and 9 show the nozzle surface temperature distribution and specific impulse-specific power characteristic, respectively.

Moderate Power Arcjets

Testing of 1 N thrusters (15 KW-class) is underway at BPD. Parametric performance mapping of a water-cooled, laboratory model engine began at IRS in 1988, under subcontract to BPD, and was completed earlier this year. Activities at BPD started with parametric testing of a water-cooled engine and are now focused on development of radiation cooled engines. Near term activities at BPD include parametric testing of several different advanced laboratory model engines with different propellants including hydrogen, ammonia, gas mixtures to simulate hydrazine and decomposed hydrazine.

A schematic of the moderate power, water-cooled arcjet tested by BPD, designated MOD-1', is shown in Fig. 10 which is similar to the MOD-1 engine tested by IRS. The engine had a segmented, water-cooled nozzle enabling variations in the nozzle and constrictor geometry. Figures 11 and 12 show a performance comparison in terms of the voltage-current characteristic and specific impulse between the MOD-1 and MOD-1' engines operating on hydrogen. Both engines showed similar performance.

Radiation-cooled 1 N arcjets are being tested at BPD. A schematic of the MOD-2 engine is shown in Fig. 13. This engine is similar to engines under test elsewhere. The voltage-current and thrust characteristics for engine operation on a gas mixture simulating hydrazine are shown in Figs. 14 and 15, respectively. Current testing activities are focused on the MOD-3A engine which is similar to the MOD-2 except that the propellant gas is injected into the plenum chamber directly through the plenum chamber wall. Thermal analysis has been conducted on the MOD-3A engine to examine the critical engine temperatures. The grid used for the analysis, along with the initial results, is shown in Fig. 16.

MPD THRUSTER DEVELOPMENT

Facilities

This section reviews the facilities at CS and UoR. Centrospazio

Facility IV2 is used at CS for testing MPD thrusters. The IV2 vacuum facility is shown schematically in Fig. 17. The facility consists of a fiberglass chamber, 0.8 m in diameter and 1.0 m in length, which permits testing of MPD thrusters with minimal electromagnetic interference from the chamber walls. The pumping system consists of a rotary roughing pump and an oil diffusion pump. This system permits operation at a background pressure of 2x10^-5 Torr with a pumping speed of 6500 l/s. The pumping system is connected to the fiberglass chamber by a gate valve. Testing conditions are normally reached within 3 hours.

The electric power equipment consists of a power supply, a pulse forming network (PFN), a ballast resistor and an igniton switch and is used to charge the PFN before each thruster pulse. The PFN consists of a ten section inductive-capacitive (LC) ladder network with a total capacitance of 12500 μF and a total inductance of 20 μH. The characteristic impedance of the network is 40 mΩ, with a pulse length 1 ms and an energy storage capability of 3.6 kJ at 2400 V. When matched with a suitable impedance, this equipment provides an approximately-rectangular, 1 ms current pulse of up to 30 kA. As a safety measure, the PFN is equipped with a dump switch. The variable ballast resistor (0 to 40 mΩ) is used in order to match the internal impedance of the PFN with the impedance of the experimental devices (MPD engines). The igniton is an electronically controlled switch which permits the discharge to trigger at the appropriate time with respect to the gas pulse in order to ensure that the discharge takes place when the injected gas mass flow rate has reached a steady value. The PFS provides carefully defined pulses of argon gas to the MPD thruster.

The diagnostic equipment used during the program included equipment for measurement of the thruster performance and electrical characteristics. The thrust stand consists of a mobile thrusting mounting piece, supported by four bars. This arrangement allows only a one degree of freedom (1-DOF) of displacement along the main thruster axis. The motion of the mobile mass caused
by a thruster shot is measured by means of a proximity transducer. The other instrumentation included two high voltage probes, a Rogowski coil, a mass flow meter for the mass flow rate calibration and two piezoresistive pressure gages for calibration of the gas feeding line. The data acquisition system consists of a transient recorder, a computer for data reduction and analysis and peripherals.

University of Rome

The vacuum facilities at UoR are based on cylindrical Plexiglass chambers pumped with oil diffusion pumps. The chamber volume is approximately 0.2 m$^3$ and has a back pressure in the range of 2 to 4 X $10^{-4}$ mbar. The PFN has available values of initial energy from 0.67 kJ to 2.67 kJ in steps of 0.33 kJ. The diagnostics include a thrust stand, Rogowsky coils with operational amplifiers, voltage probes and several Langmuir probe systems for plasma and velocity measurements.

Gas-Fed Ring Anode MPD Thruster

Gas-fed MPD thrusters are operated in a quasi-steady mode at instantaneous power levels of megawatts for several milliseconds. This research is aimed at improving the understanding of the basic physical processes involved in pure MPD acceleration mechanisms and providing design criteria for future engine designs. The test activities have been focused on exploring the effects of engine scale and geometry on the engine electrical and performance characteristics.

Three ring anode MPD thrusters are being tested at CS as shown in Fig. 18. These engines are scaled such that one engine (1:2 scale) has an anode area opening one half the size of the benchmark engine (1:1 scale) while the other engine has an anode opening area of one quarter (1:2 scale) the size of the benchmark engine. The engines can be fired up to 2 times per minute. Parametric test data on the full scale engine are shown in Figs. 19 and 20. These figures show the voltage-current characteristic (log/log) and efficiency-specific impulse ratio between the probe separation distance and the delay time. The detection of the delay time between acquisition of the signals by the two probes is the critical measurement. The plume velocity and the velocity deviation are directly related to the spacing between the probes and inversely proportional to the delay time. The velocity deviation corresponding to different values of the ratio between the probe separation distance and the delay time is given in Fig. 24.

Teflon-Fed MPD Thrusters

The present activities at UoR are focused on coaxial, non-steady, solid propellant (Teflon) MPD thrusters with instantaneous powers of a few megawatts. This work, in collaboration with CS, is being funded by MURST and ASI in two phases with the ultimate goal being to experimentally define MPD thruster laws. The first phase, which was just completed, was aimed at defining the standard parameters to be used in engine performance characterizations in order to analyze and compare non-steady systems with different discharge waveforms in the operating regime of interest. In addition, test procedures and engine geometry effects were defined. The second phase, which has just begun, is dedicated to systematic experimental evaluation of the MPD thrusters according the variables defined in first phase. The engine thrust, surface temperature and plume electronic density are also being examined.

Tests were conducted using breech-fed and radially-fed, solid Teflon propellant MPD thrusters. The engines had a segmented anode (4, 6 or 8 segments) which was either cylindrical or flared in shape. The variables included the propellant effective area (PEA), anode shape and length, anode to cathode radius ratio and the discharge waveform and power. The engine was operated over an instantaneous power range of 0.6 to 3.0 MW. The current collected by each segment of the anode is individually monitored to determine the energy distribution along the anode (see Fig. 22). The PFN has been fully modelled and experimentally characterized. Double Langmuir probes are used to monitor the plume temperature and electronic density. Figure 23 shows sampled and processed data from the double Langmuir probes. A time-of-flight (TOF) Langmuir probe system was used to measure the plume velocity. The detection of the delay time between acquisition of the signals by the two probes is the critical measurement. The plume velocity and the velocity deviation are directly related to the spacing between the probes and inversely proportional to the delay time. The velocity deviation corresponding to different values of the ratio between the probe separation distance and the delay time is given in Fig. 24.

FUTURE PLANS

The ongoing programs include arcjet engineering model development for both the low power and moderate power engines. The near-term emphasis is on the low power engine. These engine development efforts include design and thermal analysis, additional parametric testing and endurance testing with on/off cycling. The development activities will be centered on testing with decomposed hydrazine although supporting tests with gas
mixtures are planned at both BPD and CS under ASI and ESA sponsorship.

Low power arcjet propulsion system development has begun this year under ASI sponsorship. This work is being conducted by BPD with SEPA and ANSALDO serving as subcontractors. The Phase 1 program, which just has started, will last 18 months and will include a system study to define the mission and first application in detail. Additional activities include the establishment of the mission requirements and determination of the preliminary flight propulsion system configuration and subsystem requirements. The power level is expected to be between 0.5 and 1.5 kW. Detailed initial designs of all the propulsion system components will be produced. The components to be considered include the arcjet, gas generator, PCU, connecting cable, propellant storage and feed system, propulsion system controller and diagnostics. The design, fabrication and testing of a breadboard model PCU is also included in this program. Finally, the planning for the engineering model and qualification phases will be established.

The DIVA experiment has been tentatively accepted as one of the Columbus Precursor Flight Experiments and is scheduled for launch on the EURECA-3 platform in 1997. The DIVA experiment, Fig. 25, is a flight test of a 1 kW-class arcjet system to demonstrate its readiness for flight applications and will serve as a precursor to the mission identified in the study cited above. The experiment is expected to demonstrate the ΔV and on/off cycling characteristics needed for NSSK, verify system operating procedures, measure and characterize propulsion system/spacecraft interactions and validate ground test data. The near-term activities include detailed definition of the experiment.

CONCLUSIONS

New state-of-the-art facilities have been installed at BPD to enable continuous, simultaneous testing of both low power (0.5 to 2.0 kW) and moderate power (10 kW-class) arcjets. Each facility is independent of the other with dedicated pumping plants, power supplies, data acquisition and control systems and diagnostics. Facilities installation at CS has been completed for both the arcjet and MPD activities. All the support equipment has been tested and is being used for data collection.

Arcjet engine technology development is ongoing at BPD and its subcontractor, CS. Both low power (0.1 N) and moderate power (1.0 N) arcjets are under development and currently being tested. Present activities include engine operating envelope definition and parametric testing on both engine classes. Low power engines demonstrated 440 s of specific impulse using a gas mixture to simulate hydrazine. Initial test results from the radiation-cooled, 1 N-class engine have shown a specific impulse in excess of 650 s with simulated hydrazine.

Development testing of MPD thrusters is continuing at CS and UoR. Both gas-fed and solid Teflon-fed devices are under investigation. Test results to date have shown close correlation with the predicted characteristics.

Future activities include testing of both classes of arcjets on decomposed hydrazine, endurance tests with on/off cycling and engineering model development. An arcjet system definition study is being conducted to identify the first application for the low power arcjet system, conduct the initial design work for the flight propulsion system components and design, build and test a breadboard PCU. Finally, the detailed definition activities for the DIVA low power arcjet flight experiment are expected to start early next year.

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REFERENCES


Figure 1. General schematic of BPD arcjet test facilities.

Figure 2. Schematic of BPD facility VP-1.
Figure 3. Schematic of BPD facility VP-2.

Figure 4. IV3 vacuum facility at Centrospazio
Figure 5. Schematics of MOD-A and MOD-B low power arcjets.

Figure 6. Specific impulse/specific power characteristic of MOD-A on simulated hydrazine.
CALCULATED TEMPERATURE DISTRIBUTION ($T_e = 2000^\circ K$ & $T_s = 1500^\circ K$)

Figure 7. Grid and thermal analysis results for MOD-B engine.

Figure 8. Measured MOD-B nozzle surface temperature.
Propellant: N2+2H2 mixture
- 3±0.5 mg/s
- and 4±0.5 mg/s
- and 5±0.5 mg/s

Gap = 0.4 mm
Constrictor-Filled symbols: Φ = 0.62 mm; L = 0.64 mm
Open symbols: Φ = 1.01 mm; L = 0.59 mm

Figure 9. Specific impulse/specific power characteristics for MOD-B.

Figure 10. Schematic of MOD-1' water-cooled, 1 N arcjet.
Figure 11. Voltage-current characteristic comparison between MOD-1 and MOD-1' arcjets with hydrogen.

Figure 12. Specific impulse comparison between MOD-1 and MOD-1' arcjets with hydrogen.
Figure 13. Schematic of MOD-2 radiation-cooled, 1 N arcjet.

MOD-2 CHARACTERIZATION
N2+2H2 MIXTURE

Figure 14. Voltage-current characteristic of MOD-2 on simulated hydrazine.
MOD-2 PERFORMANCE
N2+2H2 MIXTURE

Specific Impulse (s)

Specific Power (J/mg)

- 150 mg/sec ±2.5 mm
- 200 mg/sec ±3.5 mm
- 250 mg/sec ±4.5 mm
- 300 mg/sec ±5.0 mm

Figure 15. Specific impulse/specific power characteristic of MOD-2 on simulated hydrazine.

Figure 16. Grid and thermal analysis results for MOD-3A engine.
Figure 17. IV2 facility at Centrospazio for MPD testing.

1:1 SCALE

1: \sqrt{2} SCALE

1:2 SCALE

Figure 18. Family of ring anode MPD thrusters.
Figure 19. Voltage-current characteristic for benchmark thruster.

Figure 20. Specific impulse-efficiency characteristic for benchmark thruster.
Figure 21. Prototype MPD heated cathode

Figure 22. Energy distribution along a six segment anode.
Figure 23. Characteristic of double Langmuir probes sampled and processed data.

Figure 24. Plume velocity deviation for different values of the ratio between the probe separation distance and delay time.
Figure 25. DIVA experiment package.