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STG-CT: High-vacuum plume test facility for chemical thrusters

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Abstract: The STG-CT, operated by the DLR Institute for Aerodynamics and Flow Technology in Göttingen, is a vacuum facility specifically designed to provide and maintain a space-like vacuum environment for researching plume flow and plume impingement from satellite reaction control thrusters. Its unique liquid-helium driven cryopump of $30\,\mathrm{m}^2$ allows maintaining a background pressure $< 10^{-5}$ mbar even when molecular hydrogen is a plume constituent.

1 Introduction

Space vehicles may control their attitude in orbit by means of a number of reaction control thrusters. These typically operate by expanding a gas through a convergent-divergent nozzle, thus converting internal into kinetic energy. Thrust is produced by expelling a rather high mass flow (on the order of grams per second) of gas at a rather low velocity (on the order of a kilometer per second). This type of reaction control thrusters shall be referred to as *chemical thrusters* to discern them from electric propulsion devices.

The plume emanating from a reaction control thruster into high vacuum expands well into the half-space upstream of the nozzle exit plane and invariably impinges on adjacent spacecraft surfaces. It is thus a source for contamination, parasitic forces and moments, and heat load. The latter two *impingement effects* are discussed in a review article by Dettleff (1991). Whether or not they are of relevant magnitude to require special attention in the design or operation of a space vehicle is typically decided by means of engineering models of the plume expansion and interaction. These plume and impingement models may be derived from experiments. Experiments become mandatory when the necessarily simplifying engineering models are expected to not capture the impingement effects with sufficient

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accuracy or when the applicability of the model is not known.

Ground-based investigation of free plume expansion requires a vacuum facility able to maintain a sufficiently low background pressure even during thruster operation. The STG-CT is specifically designed to provide and maintain a space-like vacuum environment for researching plume flow and plume impingement from satellite reaction control thrusters, cf. Dettleff & Plähn (1997) and Dettleff & Plähn (1999), but may serve in other applications as well.

2 Operation Principle

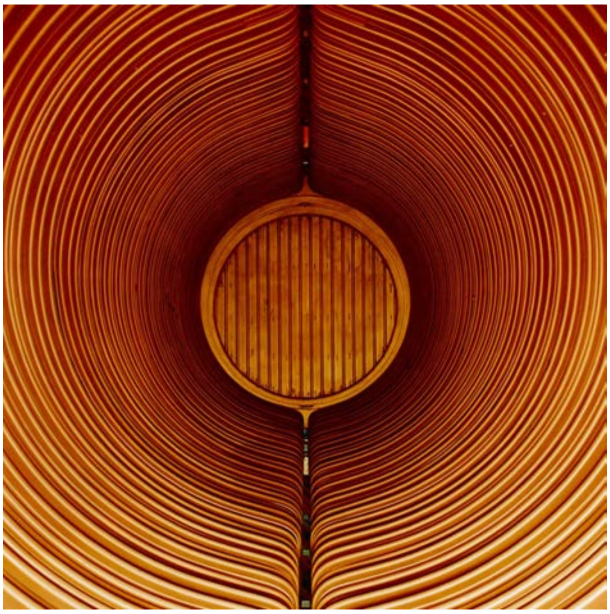

Figure 1: View into the test section.

The essential feature of STG-CT is a liquid helium-driven cryopump with an area of about 30 m^2 that almost completely encloses the test section, Fig. 1. In the ribbed pipes of the cryowall helium is kept in a boiling state at a pressure of about 1 bar, thus maintaining a wall temperature of about 4.2 K. At this temperature most technical gases (with the exception of hydrogen and helium itself) have a vapor pressure orders of magnitude lower than 10^{-10} mbar and are thus condensing to the cryowall. With hydrogen gas present in the test section a pressure less than 10^{-5} mbar can be obtained by cryopumping. As long as the cryowall temperature is kept low enough to condense the most volatile gas species under investigation, mass flow rates of the order of grams per second are permissible inside the test section without a significant increase in background pressure. The factor limiting the achievable level of background pressure thus is the energy flux imposed upon the cryowall and its cooling agent. By design, the cryopump can withstand a continuous heat load of about 500 W (short-duration peak: about 25 kW) and still maintain a wall temperature of 4.2 K.

3 Technical Description

3.1 Construction

The test section is a cylindrical room of 10 m^3 with a length of 5.25 m and a diameter of 1.6 m, enclosed by the cryowall manufactured from highly heat-conducting copper (Fig.1). The outer vacuum vessel (62.2 m^3) is made from stainless steel. A multi-layer insulation (MLI) protected sheet metal layer and a liquid nitrogen cooled surface fully enclose the inner cryopump and shield it from thermal radiation.

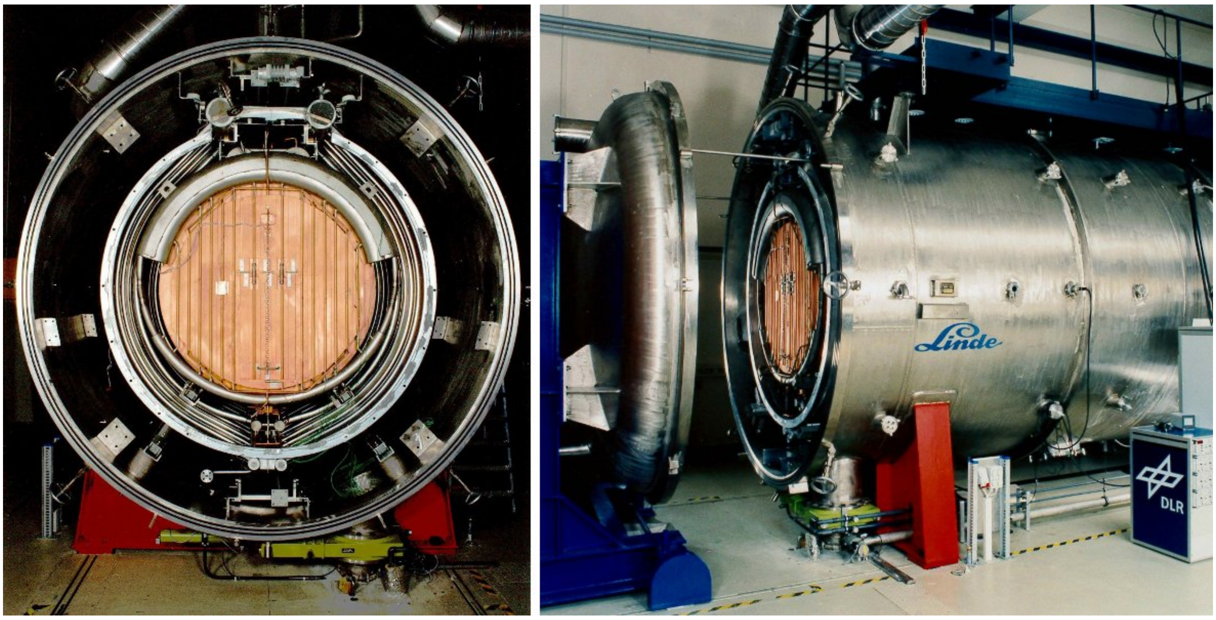

Figure 2: Front and side view of the STG-CT vacuum chamber, displaying the front face of the copper-walled test section with access door closed.

While the liquid nitrogen (pre-)cooling system is open, STG-CT is connected to a closed helium cycle. Liquid helium is stored in a cryogenic storage dewar designed to hold about $3\,\mathrm{m}^3$. From there it is pressure-fed to the cryopump, where it evaporates. The cold gaseous helium passes a sequence of electric heaters before it is compressed for storage in pressure cylinders. A liquefaction machine fills the dewar tank from the gas storage at a rate of about 20 l/h.

3.2 Access to the test section

For physical access to the test section one front face of the cryopump is equipped with a hinged door 345 mm wide and 700 mm high. These dimensions limit the size of individual pieces of the test setup, but the test section is large enough for a person to climb inside and conduct the final assembly there. A venting system is installed to supply fresh air to the test section during assembly.

Nom. diameter	Flange system	Quantity
DN50	ISO-KF	28
DN100	ISO-K	24
DN250	ISO-K	4
DN500	ISO-K	2
DN630	ISO-F	2

Table 1: Available flange connections.

The outer stainless steel vacuum vessel is equipped with a number of flange connections distributed over the surface. Table 1 lists the available flanges. Fittings to other flange systems and diameters are available or may be manufactured.

Direct mechanical and optical access is limited by the coldwalls surrounding the test section. The half-shells of the coldwalls are spaced about 30 mm, admitting a narrow-angled field of view in the vertical plane parallel to the principal axis of the test section, cf. Fig.1.

3.3 Test Cycle

Phase	Description	Duration
Evacuation	The vacuum vessel is closed and evacuated by means of a mechanical pump line (from high to low inlet pressure): • Leybold VAROVAC®S 630 F (rotary vane) • Leybold RUVAC®WAU 1000 (roots blower) • Leybold RUVAC®RA 3001 (roots blower) • Pfeiffer TPH 1500 (turbomolecular pump) to a pressure of about 10^{-3} mbar.	5 h
LN_2 cooling	Pre-cooling of the cryopump, cooling of the radiation shield to a temperature of 78 K. Pressure in the test section drops to about 10^{-5} mbar.	48 h
LHe cooling	Cooling of the cryopump to 4.2 K. Pressure in the test section drops to about 10^{-10} mbar.	6 h
Experiment	Duration depends on heat load on cryopump and amount of liquid helium available.	4 . . . 8 h
Warm-up & venting	Slow radiation-driven warming required to mitigate thermal stresses.	170 h
Liquefaction	May run in parallel to the warm-up phase.	150 h

Table 2: Phases of a typical test run in STG-CT.

Table 2 summarizes the sequential phases of a typical test run in STG-CT along with the approximate time frame for each phase. It is apparent that the cooling and warming stages limit the minimum turnaround time of the facility to about ten days per test run. The warming step may be shortened in between two consecutive runs if no changes are required to the experimental setup in the test section, but only to as much time as is required to reliquefy the gaseous helium.

4 Equipment

4.1 Actuators

STG-CT is equipped by default with two linear actuators, mounted above and below the cryopump, that run parallel to the principal axis and over the entire length of the test section. Each linear motor carries a rotary stage from which a cylindrical rod (∅ 28 mm) extends into the test section. The rods serve as mounting points for lightweight measurement devices.

4.2 Chamber Instrumentation

The copper surfaces of the cryopump are equipped at various locations with C10 resistance thermometers to monitor the temperature in the range 4 K . . . 20 K. A selection of these temperature measurements can be made available to the data acquisition system of the experiment. The background gas pressure is typically monitored by hot cathode ionization gauges (HP and Bayard-Alpert).

4.3 Sensors and Probes

Which particular sensors and probes are put to use in STG-CT of course depends largely on the purpose of the experiment and the object under investigation. Table 3 thus list only exemplarily a number of

Name	Description
Thermocouples	Ni-CrNi or PtRh types.
Pressure transducers	Various types: • capacitive, • ionizing, • piezo-resistive.
Pitot-probe	Measure total pressure (behind normal shock) in hypersonic plumes.
Patterson-probe	Measure particle flux.
Electrostatic probes	Detect electrically charged droplets in bipropellant thruster plumes.
Photo diodes	Signal light emission e. g. from combustion chamber; also serve as receiver for droplet detection in laser beam attenuation experiments.
Witness plates	Simulate spacecraft surface in contamination experiments.
Quartz crystal microbalance (QCM)	Quantitative molecular contamination analysis.

Table 3: Some measurement devices employed in plume research.

measurement devices previously employed in reseaching thruster plume expansion. For details regarding these techniques and their application refer to Dettleff & Grabe (2011).

5 Application

Examples of use cases STG-CT is particularly suited for:

- Contamination analysis with bipropellant attitude control thrusters of the 10 N-class,
- Realistic molecular contamination of surface samples,
- Investigation of material degradation through plume impingement,
- Investigation of material outgassing,
- Characterization of hot- and cold-gas thruster plumes,
- Characterization plume interference with adjacent surfaces or other plumes,
- Simulation of cold space environment,
- Functional tests of low-energy electric propulsion devices.

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