

High Enthalpy Plasma Sources for Re-Entry Simulation

Stefan Laure, Monika Auweter-Kurtz und Helmut Kurtz

Institut für Raumfahrtssysteme
Universität Stuttgart
Germany

Abstract

The qualification of modern thermal protection systems (TPS) requires the ability to duplicate and to understand the prevailing complex physico-chemical phenomena including thermal and chemical non-equilibrium near the surface of a re-entry body which enters the atmosphere of the Earth or another celestial body. At the Institut für Raumfahrtssysteme (IRS) at the University of Stuttgart four plasma wind tunnels PWK1- 4 are in operation to simulate the thermal and chemical load on the surface of a space vehicle. For the characterization of the conditions in the measurement section of these wind tunnels several diagnostic tools are in use. This paper describes the simulation range of the IRS plasma wind tunnels and the plasma sources which are in operation to generate the high enthalpy plasma flow.

Introduction

When a space vehicle returns to earth or is going to land on the surface of another celestial body, it may have extremely high velocities up to several ten kilometers per second. This causes stagnation environments, which lead to severe heating rates on the surface of the re-entry body. The task of the thermal protection system [TPS] is to reduce the resulting temperature within a few centimeters, in order to prevent overheating of the space vehicle. The conditions on the surface of a space craft, which enters the earth atmosphere are dominated by the shock wave in front of it. For example during Appollo re-entry the gas temperature reached approximately 11,000 K at a Mach number 36. It is possible to simulate approximately the real gas composition in front of the spacecraft for a few ms in so- called hot shot or piston shock tunnels [1]. Since the duration of the tests in these facilities is far too short to heat up the surface of a material sample, thus preventing an interaction between the material sample and the hot gas under realistic conditions, these facilities are unsuitable for the development and qualification of thermal protection materials. The qualification of heat protecting materials for space transportation systems requires the duplication of surface conditions as accurately as possible. In order to investigate the

erosion of TPS - materials it is necessary to simulate these conditions over a long period of time. This work has to be done in continuously running plasma wind tunnels [1].

For the re-entry of a winged space craft the conditions plotted in Figure 1 have to be simulated in the measurement range of the IRS section of the plasma wind tunnel, here compared with the simulation range of the IRS plasma wind tunnel PWK.

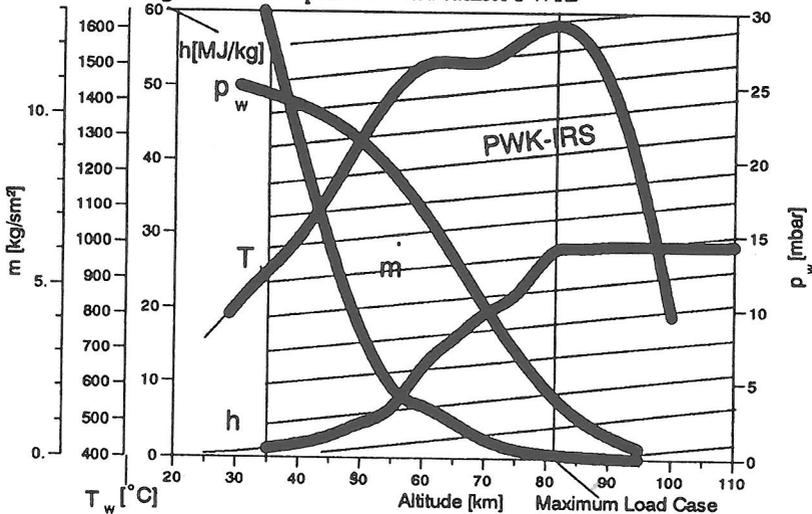


Fig. 1: Surface temperature, pressure, specific enthalpy and the mass flow rate at the leading edge of HERMES during reentry for landing in Cayenne. (Thick lines: simulation region with PWK; hatched zone: simultan. simulation with PWK).

2 IRS - Facilities and Plasma Wind Tunnels

The facilities at the IRS needed to run the plasma wind tunnels and the plasma sources which are in operation are described in the following sections briefly.

2.1 Vacuum System and High Current Supply

In order to simulate pressures at altitudes up to 90 km, a four staged vacuum pump system is used. The total suction power of the pumps amounts to 6000 m³/h at atmospheric pressure and reaches about 250,000 m³/h at 10 Pa measured at the intake pipe of the system which has a diameter of 1 m. The desired tank pressure can be adjusted between the best achievable vacuum and 1 bar. Eight vacuum tanks of different sizes are connected to this system, four of which serving as the plasma wind tunnels PWK1-4. The current for the operation of thermal plasma generators [TPG] and magnetoplasmadynamic generators [MPG] is supplied by a current regulated thyristor rectifier consisting of six identical units supplying 1MW each. These may be connected in series or in parallel, thus varying the desired output level. The ripple of

the current is less than 1%. The maximum current is 48 kA d.c. supplied at 125 V and the maximum voltage is 6000 V at a current of 1000 A.

2.2 Plasma Wind Tunnels

Until 1989 the plasma wind tunnel PWK1 was the only available facility of this type for re-entry simulations in Europe. Since 1987 it has been used for the development of thermal protection materials especially for the now defund European mini-shuttle HERMES. A second plasma wind tunnel PWK2 was built in 1990. The third, inductively heated, plasma wind tunnel PWK3 was installed in the year 1994. In order to enlarge the pressure range a fourth plasma wind tunnel equipped with a coaxial thermal plasma generator was put in operation at the beginning of the year 1995. In the IRS - wind tunnels three different kinds of acceleration mechanisms are applied to generate a high enthalpy plasma flow. As sketched in Figure 3 the plasma sources for the generation of the high enthalpy flow are fixed in the cover of the vacuum tanks used as plasma wind tunnels.

2.2.1 Plasma Wind Tunnels PWK1 and PWK2

PWK1 and PWK2 are equipped with MPGs, which may be operated in a power range between 50kW and 1MW. They are suitable tools for the simulation of the first entry phase of a re-useable winged spacecraft which enters the Earth's atmosphere. During this flight phase the surface pressure is low, the velocity of the spacecraft and the specific enthalpy of the gas composition the space vehicle is exposed to are high. The erosion of oxidation protected materials is expected to be at a maximum during this phase. The capability to produce gas flows on an enthalpy level up to several hundreds of MJ/kg can be used to duplicate the stagnation point flow field of very fast space vehicles expected for the reentry flight of a comet sample return probes like ROSETTA, as it was planned in a former version, or of a MARS return probe[2].

The investigation of the erosion behaviour of modern TPS - materials based on C-C or C/SiC requires detailed information of the state of the gas composition on the surface of the heat shield during the re-entry flight and during PWK simulation. The main task of the MPG-wind tunnels during the last year was the simulation of the maximum load case caused of a winged space craft by a flight environment characterized by the following parameters: a velocity of 7452 m/s at an altitude of 81.3 km, which corresponds to a specific enthaply of about 28 MJ/kg. The mass flux and total pressure expected are 0.117 kg/m²s and 4 mbar, respectively (Fig. 1). The high enthalpy plasma flow which simulates this flight case was investigated at the IRS during the last years [3]. Therefore several diagnostic tools are in use. The properties in the plasma jet are determined using various diagnostic methods. Mechanical probes are in use to determine pitot pressure, static pressure, specific enthalpy and the heat flux to the surface of a material sample. Cylindrical electrostatic single-, double-, triple and time of flight probes are applied for the measurement of the temperature distributions of ions, electrons and the heavy particles velocity. In order to verify the results achieved with electrostatic probes a Fabry-Perot-Interferometer is used. The measurement techniques were applied for the determination of the flow properties at

two cross sections of the high enthalpy air flow. The results of the first cross section serve as initial and boundary conditions for the numerical calculation of the flow field. The measured values of the second cross section give the possibility to compare them with the calculated values and so to validate the code.

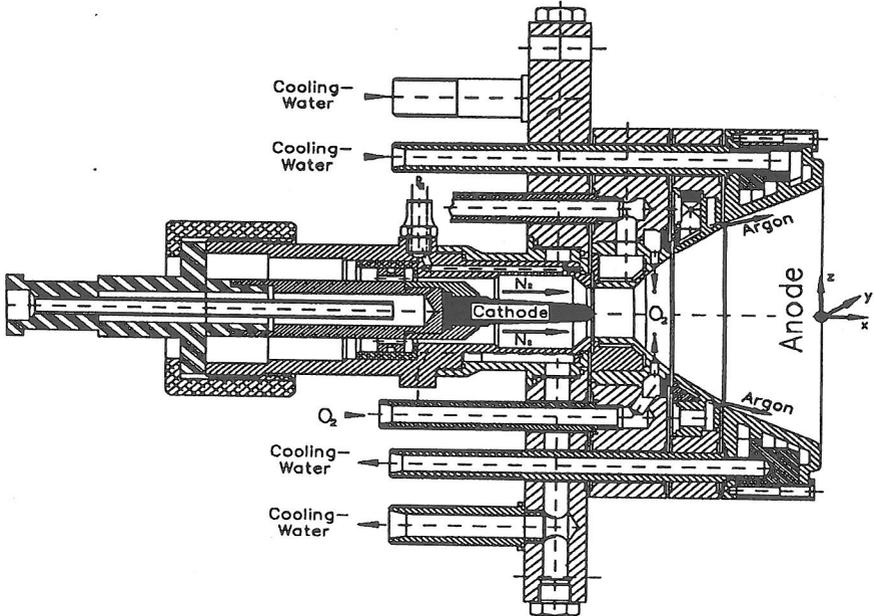


Fig. 2: Scheme of a Magnetoplasmadynamic Generator.

The MPGs used at IRS consist of two coaxial electrodes, separated by water cooled copper segments. The nozzle exit which is also a water cooled, forms the anode. The cathode is made of 2% thoriaed tungsten and is mounted in the plenum chamber. In order to avoid a spotty arc attachment on the anode, thus causing a contamination of the plasma free jet, a small amount of argon is injected tangentially along the anode contour. With this method it could be shown experimentally that no anode erosion takes place. The only contaminating part is the cathode. During continuous operation the cathode is heated up to more than 2500 °C. The high temperature and the low work function results in a diffuse arc attachment and consequently in a low cathode erosion rate. But even this tiny cathode erosion, which is about equal to the sublimation rate, may substantially influence the catalytic behaviour of TPS-material under heat load.

2.2.2 Plasma Wind Tunnel PWK3

In case of PWK3 [4] an inductively coupled discharge is used to generate the high enthalpy flow. Since in MPGs the plasma is in contact with metallic electrodes, a contamination of the plasma by electrode-erosion products, which influences the catalytic of the material samples, may occur. Therefore PWK3 is used for the

verification of experiments carried out within PWK1 and PWK2 and for basic research especially on the catalytic behaviour of thermal protection materials.

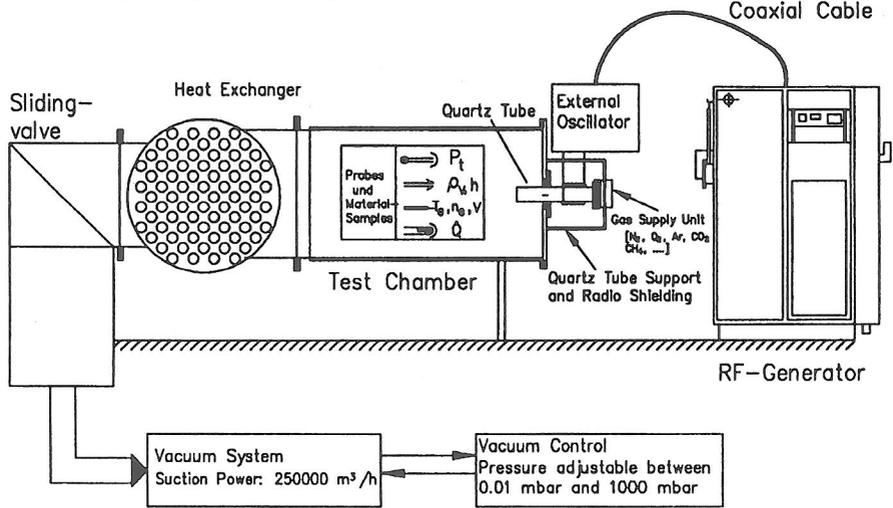


Fig. 3: Scheme of PWK3

The induction heated plasma wind tunnel is equipped with a 150 kW RF-generator, which is designed to operate at a nominal frequency of 650 kHz.

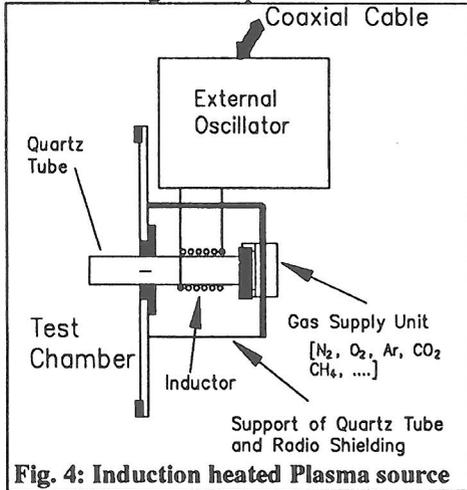


Fig. 4: Induction heated Plasma source

A power oscillator is connected to the load circuit by 5 coaxial cables of 6m in length. It supplies a high frequency current into the external oscillator, which represents the plasma source. The load circuit is a parallel resonant circuit consisting of the inductor, which is at present a water cooled copper coil with five or seven turns and the capacity, which is built of one to seven capacitors connected in parallel. The inductor surrounds a quartz tube of 96 mm in diameter. The open end of the quartz tube is connected to the test chamber. The other end is closed and equipped with the gas supply unit, which allows the operation of the plasma source with

different gases or gas mixtures. The experimental setup of the plasma source is shown in Figure 4.

2.2.3 Plasma Wind Tunnel PWK4

The working principle of the MPGs of the PWK1 and PWK2 limits their use to a stagnation pressure of about 50 mbar. In order to simulate high enthalpy air flows in a

pressure level above 50 mbar in an heat flux range between 100 kW/m^2 and about 3 MW/m^2 , in PWK4 a coaxial TPG of the type RB2 (Fig. 5) is used to accelerate the working gas. The test gas is heated in the discharge chamber by an electric arc and accelerated in a nozzle. In the present case the cathode is also made of 2%thoriated tungsten. The anode is a water cooled copper cylinder which allows the injection of oxygenic gases. Since the contact between the oxygenic part of the test gas and the cathode has to be avoided, different efforts have been performed to achieve electrode erosion rates the the same range as in MPGs. Therefore, the air used for re-entry simulation is divided into three parts. The main part of the nitrogen is passed along the cathode into the plenum chamber. The oxygen part is injected in nozzle throat To ensure a complete mixing of nitrogen and oxygen, this has to be done in the subsonic part of the TPG, so a back flow of oxygen into the cathode region could happen. In order to operate the glowing cathode in pure nitrogen atmosphere a small part of this gas is fed through the hot tungsten part of the cathode. It was shown that the cathode erosion rate for the RB2 is in the same range as for the MPGs operated at the IRS.

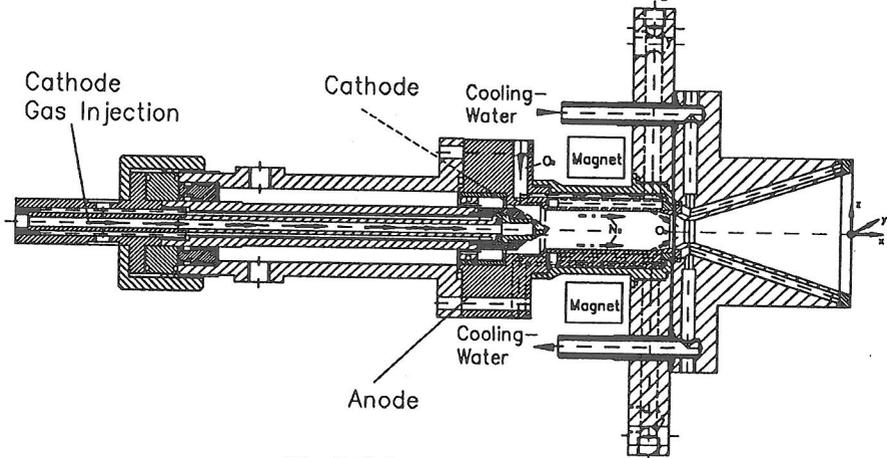


Fig. 5: Scheme of TPG RB2

References

- [1] John A. Lordi, "Aerothermodynamic Facilities and Measurement", AIAA Professional Study Series, Colorado Springs, Colorado, June 18-19, 1994
- [2] S. Laure, M. Auweter-Kurtz "Experimental Simulation of the Stagnation Point Flow Field of an Aerobraking High Velocity Reentry Vehicle within a Plasma Wind Tunnel" AIAA 94-2569 18th Aerospace Ground Testing Conference, Colorado Springs, June 20-23, 1994
- [3] H. Habiger, M. Auweter-Kurtz, S. Fasoulas, S. Laure, A. Schönemann "Investigation of a High Enthalpy Air Flow within a Plasma Wind Tunnel" 6th AIAA/ASME Joint Thermophysics and Heat Transfer Conference, Colorado Springs, June 1994
- [4] Laure S., Auweter-Kurtz, M., Fasoulas, H. Kurtz "Reentry Simulation within an Induction Heated Plasma Wind Tunnel", 2nd Europ. Symp. on Aerothermodynamics for Space Vehicles, ESTEC, Noordwijk, NL, 22-25 Nov. 1994