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Plasma Generators for Re-Entry Simulation

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The qualification of thermal protection systems (TPS) and numerical design tools for re-entry vehicles and space probes requires the ability to understand and duplicate the prevailing complex physico-chemical phenomena, including thermal and chemical nonequilibrium near the surface of a body that enters the atmosphere of the Earth or another celestial body. At the Institut für Raumfahrtsysteme of the University of Stuttgart, four plasma wind tunnels (PWK1-4) are in operation to simulate the thermal, aerodynamic, and chemical loads on the surface of a space vehicle. Three different plasma sources have been developed for this purpose: 1) a magnetoplasmadynamic generator for the simulation of the high-enthalpy and low-pressure environment during the first phase of re-entry, 2) a thermal arcjet device for the follow-on flight path at moderate specific enthalpies and higher stagnation pressures, and 3) an inductively heated generator for basic materials experiments over a wide range of specific enthalpies and pressures. Special efforts were made to avoid electrode erosion to preclude impairing the erosion and catalytic behavior of TPS materials. A detailed description of these plasma generators and an overview of the simulation regions and operation areas of the plasma wind tunnels are presented.

Introduction

A VARIETY of devices are in use for ground-based simulation of re-entry phenomena to acquire the understanding necessary for the design of modern reusable re-entry vehicles and space probes and for the qualification of thermal protection systems. Shock tubes and tunnels have been built for the investigation of real gas effects,[1,2] but because of their short operation time, a full characterization of the gas conditions necessary for code validation is laborious and costly; moreover, they cannot be used for material qualifications that need the duplication of the full thermal load over the mission time. For these purposes plasma wind tunnels of different sizes and operation areas are in use in the U.S.,[3-5] Japan,[6,7] Russia,[8] and Western Europe.[9-11] Large facilities for the region of moderate specific enthalpy and high stagnation pressure are used for investigations of large models and for qualification of materials under aerothermodynamic load. They are equipped with thermal arcjet devices of the Huels- or constrictor type[3,4,9] and can be operated up to a power level of 100 MW for several minutes, some of those even for hours.

Much smaller facilities[6,7,12,13] are adequate for the investigation and qualification of thermal protection system (TPS) materials and for the validation of aerothermodynamic codes. For the work described in this report, four medium-size plasma wind tunnels, dubbed PWK (plasmawindkanal) have been built. They can be run from 40 kW up to the megawatt level continuously, creating a plasma jet with diameters between 100–350 mm at specific enthalpies up to 150 MJ/kg, and stagnation pressures in the range from 10 Pa to several 10 kPa. These devices are designed for the European projects described in the next section and equipped with plasma generators of different types to meet the qualification requirements of fiber ceramic and ablative materials for these missions[14-16] as well as for scientific materials investigations[14,17] and code validation.[18-20] Magnetoplasmadynamic (MPD), thermal arcjet, and inductively heated generators have been developed, based on the experience with a large variety of plasma thrusters.[21] Numerical design tools for further improvement of these plasma generators are under development, based on the numerical experience in plasma thruster modeling.[22-24] Special emphasis was placed on the minimization of gas impurities, which is of great importance for the investigation of the erosion behavior and the catalycity of the TPS materials, the latter strongly influencing the heat input during re-entry maneuvers. For the qualification of a plasma wind tunnel for the work previously described, a detailed experimental and numerical analysis of the composition and condition of the high-enthalpy gas flow is required.[25-29] Therefore, several experimental measurement techniques and numerical tools have been developed for the wind tunnels described in this article.[20,30-34]

Simulation Requirements in Europe

The requirements for re-entry simulation of European spacecraft, which can be covered partly by medium-size plasma wind tunnels, will be illustrated with four examples: 1) the now defunct Space Shuttle project Hermes, 2) the Express ballistic capsule, 3) the semiballistic capsule project Colibri, and 4) the Huygens scientific probe mission that will enter the atmosphere of Saturn's moon Titan.

Hermes Space Vehicle

During the first phase of re-entry, the Hermes vehicle was expected to be exposed to high specific enthalpies at a low level of stagnation pressure, as shown in Fig. 1 for the leading edge. The maximum temperature of about 1600°C (with the assumption of a fully catalytic material) was expected at a specific enthalpy of ~30 MJ/kg and a stagnation pressure of ~400 Pa. At 2500 Pa, the temperature is reduced to less than 900°C. Carbon–carbon (C–C) or silicon–carbide (C–SiC) were planned as TPS oxidation-protected ceramic materials. Because of active oxidation, the erosion of these materials is high at low pressure and high temperature.[35] This is the case for the first flight path of Hermes.[14,15] As discussed later, the re-entry specific enthalpy, stagnation pressure, and corresponding mass flux rate can be simultaneously simulated within the plasma wind tunnels PWK1 and PWK2, which are equipped with so-called MPD generators. These wind tunnels have been used for most of the qualification work for the Hermes TPS, and the tests for the Japanese space plane Hope are in prepa-

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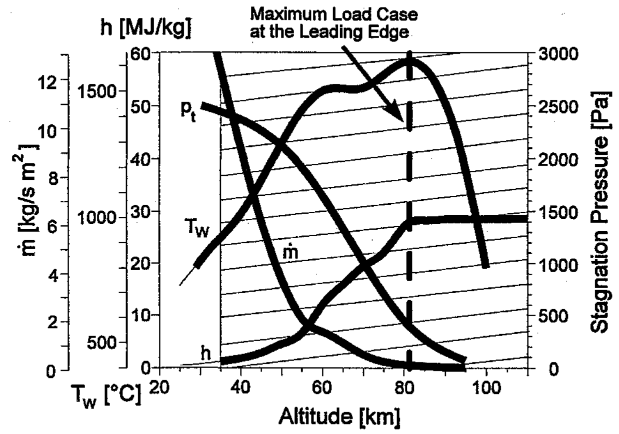

Fig. 1 T_w, p_t, h, and $\dot{m}$ at the leading edge of Hermes during re-entry for landing in Cayenne. (Thick lines, simulation region with PWK1 and hatched zone, simultaneous simulation with PWK1.)

ration, for which the simulation requirements are similar because of the similar sizes of these vehicles.

Since the interest of the European space policy has shifted away from the winged space plane to re-entry capsule projects, the simulation requirements have also changed. In contrast to the space plane projects, where high specific enthalpies of about 30 MJ/kg have to be simulated at low stagnation pressures in the range between about 4–3500 Pa, for capsule projects the maximum load case occurs at lower altitudes of about 40 km. For this reason the maximum load case is shifted to higher pressures in the range of more than 20 kPa at lower specific enthalpies. To simulate high stagnation pressures at moderate heat flux levels, the coaxial thermal plasma generator RB2 (described later) has been developed.

Express Capsule

The conditions expected for the German–Japanese re-entry mission Express[16] are plotted in Fig. 2. The maximum heat flux was calculated to be ~2 MW/m² at a stagnation pressure of ~80 kPa. The ablative heat shield was built by the Russian company Khrunichev, but for the German and Japanese re-entry experiments, a 300-mm-diam ceramic tile made of C–SiC material was inserted, which had to be qualified within the PWK. The heat flux profile was simulated in PWK2 and the maximum temperature (2600°C) of the tile was determined during this experiment. The required pressure level for a complete simulation of this flight path could not be achieved with the MPD generator available during the qualification phase of Express in 1993. For such missions the newly developed thermal arcjet can be used in the future.

Colibri Capsule

An example of the calculated conditions for the semiballistic Colibri capsule project[36] are shown in Fig. 3. The maximum heat flux of ~2.2 MW/m² is expected at a stagnation pressure of 20 kPa and a corresponding specific enthalpy of 26 MJ/kg. These conditions are well within the simulation region of the plasma wind-tunnel PWK4, equipped with the thermal plasma generator.

Huygens Probe

The qualification of the TPS material for the space probe HUYGENS within an arc-driven plasma wind tunnel was very difficult because of the chemical composition of the atmosphere of Saturn's moon Titan. It contains ~80% N_2, 1–10% CH_4, and possibly ~10% Ar. Dealing with carbon containing gases within plasma generators is difficult because of the forming of carbides with hot metallic parts such as the cathode and the formation of carbon layers (soot) on the surface of the cold electrodes and insulators. These problems were solved using

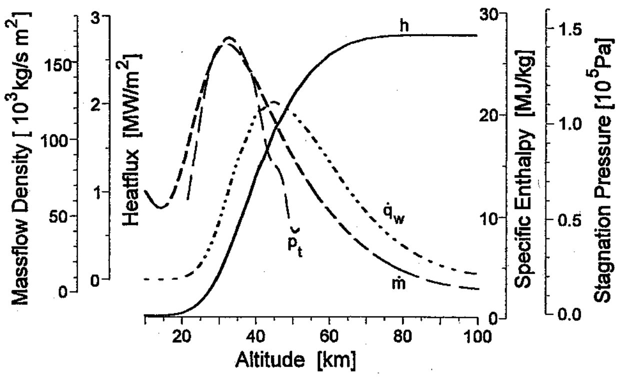

Fig. 2 $\dot{q}_w$, p_t, h, and $\dot{m}$ at the stagnation point of Express during re-entry.

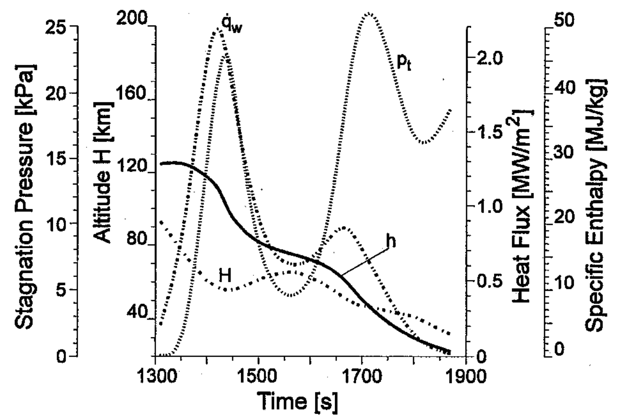

Fig. 3 Flight altitude, $\dot{q}_w$, p_t, and h at the stagnation point of Colibri during re-entry.

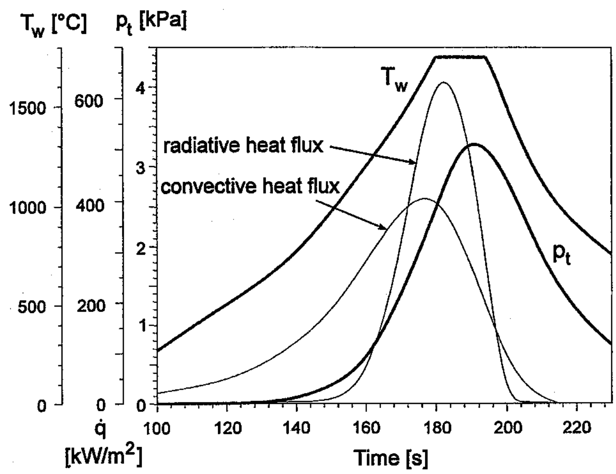

Fig. 4 p_t, T_w, and radiative and convective heat fluxes at the stagnation point of the Huygens probe during Titan entry.

the PWK2[37]; and the point of maximum heat flux of ~1 MW/m² at a stagnation pressure of ~3 kPa (see Fig. 4) has been achieved. The new inductively coupled PWK3 can now be used with carbon containing gases or even tests with pure CH_4, CO_2, or O_2. However, this wind tunnel was not available when this qualification work was performed in 1992.

Facilities

The wide range of re-entry conditions that must be simulated requires a correspondingly wide range of test facilities. The vacuum system and power supply units available at the Institut für Raumfahrtsysteme for plasma wind-tunnel operation are described briefly next.

Power Supplies

The electric power for the plasma generators of the wind tunnels PWK1, PWK2, and PWK4 is supplied by a current-regulated thyristor rectifier consisting of six identical units supplying 1 MW each. These may be connected in series or in parallel, thus varying the desired output level of current, voltage, and power. The current ripple is less than 0.5%. The maximum current is 48 kA supplied at 125 V and the maximum voltage is 6000 V at a current of 1000 A.

For the inductively heated plasma wind-tunnel PWK3 a radio frequency generator with a primary power of 400 kW is used. This device allows the operation of an induction-coupled plasma generator with a coil power of 150 kW at a nominal frequency of 650 kHz. An external resonance circuit is designed for an optimal coupling into the plasma over a wide pressure range with different gases.

Vacuum System

A vacuum pump system is used to simulate pressures at altitudes up to 90 km. This pumping system consists of four stages: the first two stages consist of roots blowers, the third stage is a multiple-slide valve-type pump, and the last stage (pumping up to atmospheric pressure) is a rotary-vane-type pump. The total suction power of the pumps amounts to 6000 m^3/h at atmospheric pressure and reaches about 250,000 m^3/h at 10 Pa measured at the intake pipe of the system, which has a diameter of 1 m. The base pressure of the system is 0.5 Pa. The desired tank pressure can be adjusted between the best achievable vacuum and 100 kPa by removing one or more pumps out from the circuit and/or mixing additional air into the system close to the pumps.

Eight vacuum tanks of different sizes are connected to this system, four of which serve as the plasma wind tunnels PWK1–4, the others for plasma thruster development.

Plasma Wind Tunnels

The plasma wind tunnels PWK1 and PWK2 are both roughly 6 m in length and 2 m in diameter. As an example, a schematic of PWK2 is shown in Fig. 5. Windows for spectroscopic diagnostics are installed on three sides of the tank, enabling the measurement of the whole plasma jet, starting from the exit section of the plasma source downstream. The tanks are made of stainless steel to prevent corrosion caused by atomic oxygen. They are equipped with a water-cooled double wall to withstand high heat flow rates. An additional cooling system is mounted at the end of each tank to cool the gas to prevent damage to the vacuum system. To protect all devices that come in contact with the hot plasma against damage by the heat load, they can be connected to two special cooling water supplies, which provide cooling water at pressures of ~2 and 6 MPa, respectively. PWK1 and PWK2 are both equipped with four-axis positioning systems for material or

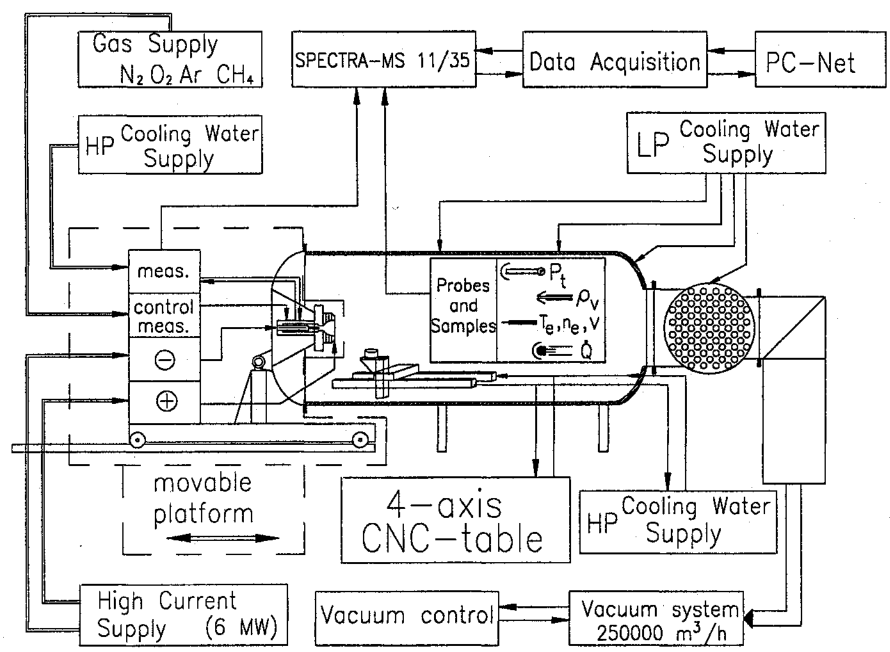

Fig. 5 Scheme of PWK2.

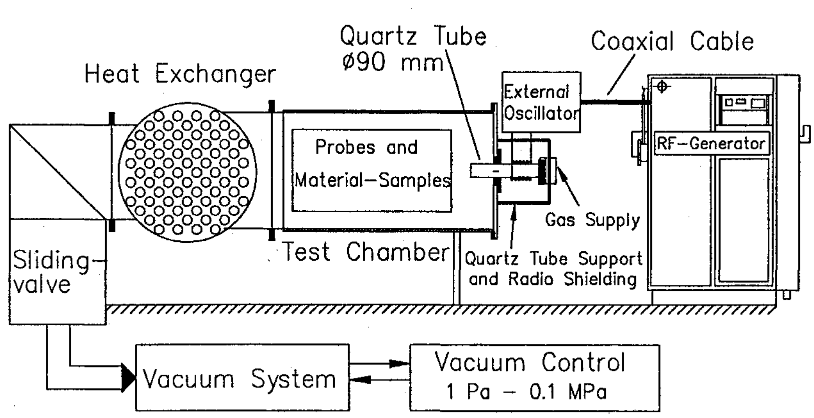

Fig. 6 Scheme of PWK3.

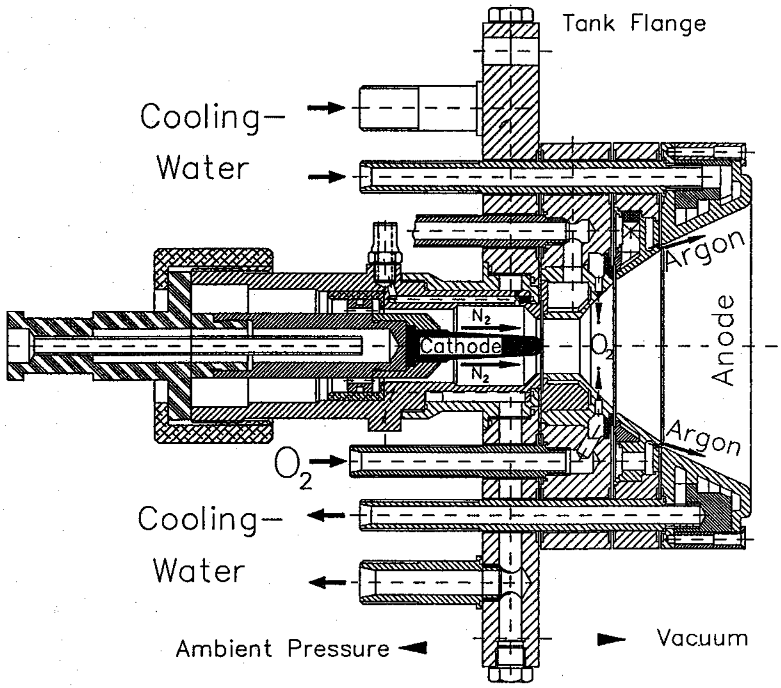

Fig. 7 Plasma generator RD5 (nozzle exit diameter 125 mm).

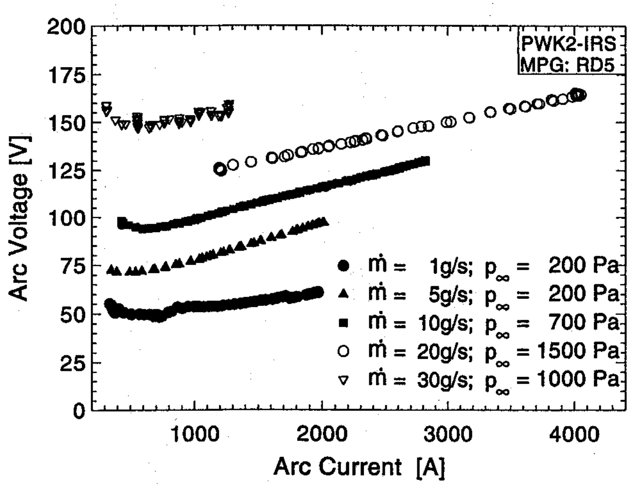

Fig. 8 Current voltage characteristic of RD5.

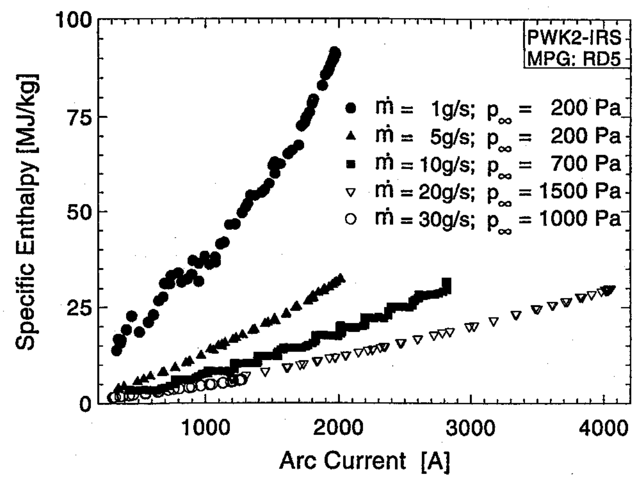

Fig. 9 Average specific enthalpy at nozzle exit as a function of the arc current for RD5.

measurement probes. The plasma wind tunnels PWK3 (see Fig. 6) and PWK4 are also connected to the vacuum and high-pressure cooling water systems described previously. Power is supplied by an rf-generator and a dc-power supply, respectively. Both PWK3 and PWK4 are installed in smaller vacuum tanks of, respectively, 0.8 and 1.2 m in diameter. They are equipped with a positioning system that allows the probes or material samples to be moved along and perpendicular to the jet axis.

Magnetoplasmadynamic Generator

Since high-specific enthalpies are required at a low power level for TPS qualifications for vehicles like Hermes[14] (see Fig. 1), so-called magnetoplasmadynamic generators (MPG) have been developed for the plasma wind tunnels PWK1 and PWK2, based on the experience gained in the investigation of high-power (MPD) thrusters.[38] The nozzle-type MPG plasma generators (dubbed RD) (Fig. 7) consist of two coaxial electrodes, separated by neutral, water-cooled copper segments. The nozzle exit, which is also a water-cooled copper segment, forms the anode. The cathode, made of 2% thoriated tungsten, is mounted in the plenum chamber.

The arc is ignited by Paschen breakdown. Current passes through the expansion nozzle from the tip of the cathode to the end of the nozzle. The test gas is dissociated and partly ionized. To avoid oxidation of the cathode, only the nitrogen component of the test gas is fed in along the cathode into the heating chamber, heated up by the arc and accelerated partly by the thermal expansion and the electromagnetic forces because of the self-induced magnetic field in the nozzle. The magnitude of the magnetic acceleration force strongly depends on the current level of operation.[39] With this MPG, the oxygen needed for the duplication of high enthalpy airflows is fed in radially at a high velocity at the supersonic part of the nozzle, but still within the arc region. The various gas injection points enable the operation of the MPG with different gas mixtures. As pointed out earlier, this capability is used for the investigation of entry maneuvers into the atmospheres of other celestial bodies such as Titan and Mars, containing CH_4 and CO_2, respectively.

Special efforts have been made to minimize the erosion of the plasma generator. Therefore, to avoid spot-arc attachment on the anode, which would cause contamination of the flow, a small amount of argon is injected tangentially along the an-

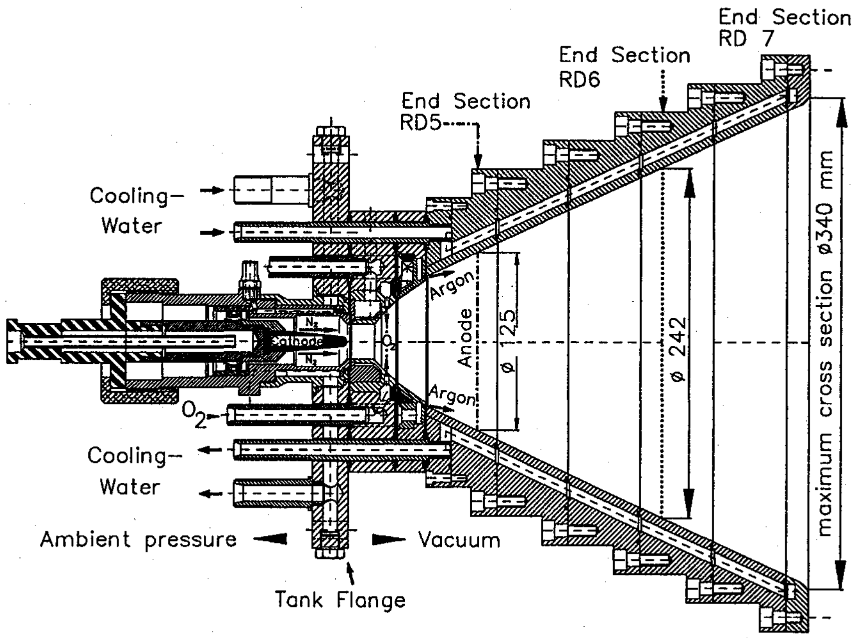

Fig. 10 Plasma generators RD5 (nozzle diameter 125 mm), RD6 (nozzle diameter 242 mm), RD7 (nozzle diameter 340 mm).

ode contour. This method has been shown experimentally to eliminate anode erosion. Within the whole region of operation the only contaminating part of the MPG is the cathode. The 2% thoriated tungsten cathode reaches more than 3000 K during operation.[40] The high temperature and low work function of the cathode results in a diffuse arc attachment and, consequently, a very low cathode erosion rate compared with those of the thermal plasma generators running with cold cathodes. Furthermore, the very low cathode erosion results in operation periods of the MPG of hundreds of hours without refurbishment of the generator.

The MPGs are operated at ambient pressures between 5 Pa and 5 kPa. For RD5, with a nozzle exit diameter of 125 mm, the mass flows are between 0.3–50 g/s at current levels between 200–4000 A and power levels of 40 kW to 1 MW, whereas the average specific enthalpy varies between 2–150 MJ/kg.

The current–voltage behavior and the corresponding average specific enthalpies are plotted in Figs. 8 and 9. Raising the mass flow increases the arc voltage and decreases the specific enthalpy; raising the current increases the arc voltage as well as the specific enthalpy. The thermal efficiency of the MPG, which is defined as the ratio of the plasma jet power to the electrical input power, varies between 70–85%, improving with increasing mass flow rate, but showing nearly no dependency on power over a wide range of operation.[11]

For the qualification of larger parts, the nozzle has been extended to 242 mm in the case of RD6 and 340 mm in the case of RD7 (see Fig. 10). Figure 11 shows a radial heat flux profile for the RD7 with 10 g/s N_2/O_2 mass flow at 3100 A at a position 280 mm downstream of the nozzle exit.

To change the conditions in the measurement section of the plasma jet, there are four adjustable parameters that influence the state of the plasma in the freejet. These are: the arc current I, the mass flow rate $\dot{m}$, the ambient pressure p_∞ in the measurement section, and the distance x of a probe tip or a material sample to the end section of a plasma source.

There are several approaches to enlarging the stagnation pressure range of the MPGs. For example, the behavior of stagnation pressure and surface heat flux is plotted as a function of the arc current in Fig. 12. An increase of current or a decrease of the distance to the plasma source results in higher stagnation pressure, specific enthalpies, and surface heat flux. It is possible to simulate stagnation pressures of more than 10 kPa if the arc current is increased. These high-pressure and high-specific enthalpy conditions are required for missions such as the re-entry of a Mars return probe or a comet sample return probe.[41,42]

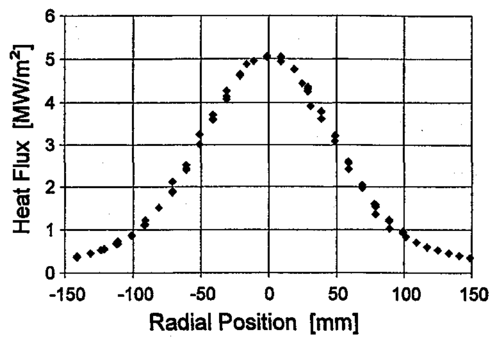

Fig. 11 Radial heat flux profile of RD7 at 10 g/s mass flow, 3100-A arc current, 14-Pa ambient pressure, 280 mm from nozzle exit.

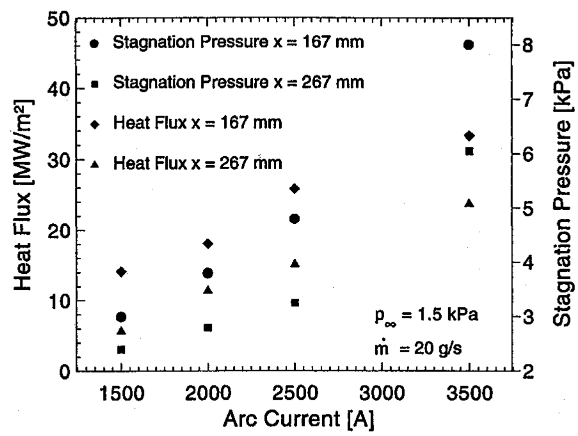

Fig. 12 Stagnation pressure and surface heat flux as a function of the arc current (RD5).

Inductive Plasma Generator

For additional investigations of the catalytic behavior and erosion mechanisms of TPS materials, a plasma wind tunnel with an induction-coupled plasma generator has been built. Its advantage over those with arc-heated plasma generators is the electrodeless operation, which results in very high purity of the plasma and allows the use of pure oxygen and carbon-containing gases. In the case of PWK3, the rf generator described earlier supplies the induction plasma generator (IPG). As schematically shown in Fig. 6, it consists of an external resonance circuit, including the inductor, a gas supply unit, a quartz tube as plasma plenum, and for special cases, an additional nozzle. The power is supplied to the resonance circuit by means of five coaxial cables. The resistance of the plasma depends on the working gas, the pressure in the quartz tube, and on the power level. By changing the number of capacitors or the number of turns of the inductor coil, the frequency can be changed between 400–900 kHz and adjusted to optimize the energy input into the gas. The ignition of the plasma takes place because of the induced electric field in the working gas without requiring any additional measures within a pressure range of 50 to ~1500 Pa.

The first experiments for material investigations duplicated the Hermes test case (see Fig. 1) to compare it with the results obtained in the other PWKs. In case of the inductively heated plasma wind tunnel PWK3, the adjusted parameters for material tests are anode voltage at the triode of the rf generator, mass flow rate, ambient pressure, and distance of the material probe to the end section of the quartz tube. The measured stagnation pressure and the heat flux to a copper probe positioned at the centerline of the jet as a function of the anode voltage at the triode for an ambient pressure of 100 Pa and mass flow rate of 1 g/s at a distance of 10 mm to the exit

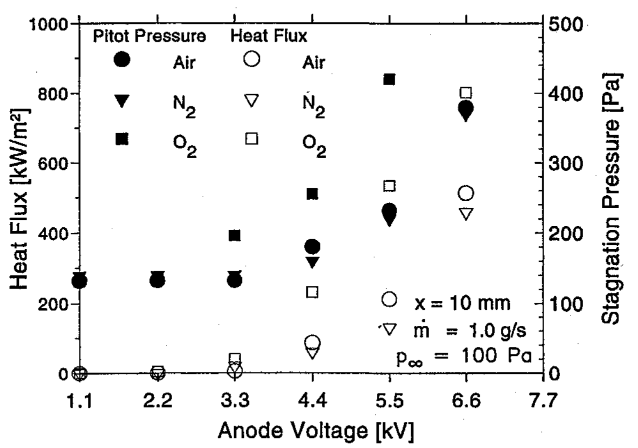

Fig. 13 Heat flux and stagnation pressure in the center of the plasma jet in PWK3 as a function of the anode voltage at the triode.

plane of the plasma generator are shown in Fig. 13 for air, pure nitrogen, and pure oxygen. These pressure and heat flux results were used to calculate specific enthalpy using Pope's theory.[43] The test conditions required for Hermes (see Fig. 1) could be achieved with an anode voltage of 7.2 kV, a mass flow rate of 1 g/s air at a distance of 10 mm.

Thermal Plasma Generator

The operating principles of the PWK1 and PWK2 MPGs limit their use to situations where the stagnation pressure is less than about 5 kPa. To simulate high-enthalpy airflows at pressure levels above 5 kPa and in heat flux ranges between 100 kW/m^2 and about 3 MW/m^2, a coaxial thermal plasma generator (TPG) called RB2 (Fig. 14) has been developed for the PWK4. The test gas is heated in the discharge chamber by an electric arc and accelerated in a nozzle. In the present version a 2% thoriated tungsten cathode is used. The anode is a water-cooled copper cylinder, whereas the nozzle is electrically isolated. Since contact between the oxygenic part of the test gas and the cathode has to be avoided, the air used for reentry simulation is divided into three parts. The main part of the nitrogen is passed along the cathode into the plenum chamber. The oxygen is injected at the downstream end of the anode toward the nozzle throat. To ensure good mixing of nitrogen and oxygen, the injection point is positioned in the subsonic part of the TPG, so that a backflow of oxygen into the cathode region cannot be ruled out completely. However, tests have shown that the cathode erosion rate for RB2 is as low as observed in the MPGs operated in PWK1 and PWK2. To avoid anode erosion caused by to spot arc attachment, a coil is used to generate an axial magnetic field that spins the arc.

As with the MPG wind tunnels, the adjustable parameters in RB2 are the arc current, mass flow rate, ambient pressure, and the distance to the exit of the plasma source. The arc voltage is almost constant with rising arc current and is in the order of 120 V, increasing with mass flow. The thermal efficiency is about 65–70%, with a mass flow rate of 5 g/s and about 75% with 10 g/s. It decreases slightly with increasing current caused by the increase of pressure in the arc chamber, whereas the specific enthalpy increases (see Fig. 15). The arc chamber pressure, which determines the maximal expansion ratio, is in the order of 50–100 kPa, increasing with mass flow and arc current.

The conditions in the measurement section of PWK4, namely, the stagnation pressure, the heat flux measured with a cold copper probe, and the corresponding local specific enthalpy calculated with Pope's theory,[43] are plotted as functions of the ambient pressure in Figs. 16 and 17 for two different mass flow rates. With 5 g/s (Fig. 16) at an ambient pressure of 450 Pa, the maximal heat load situation of the Japanese

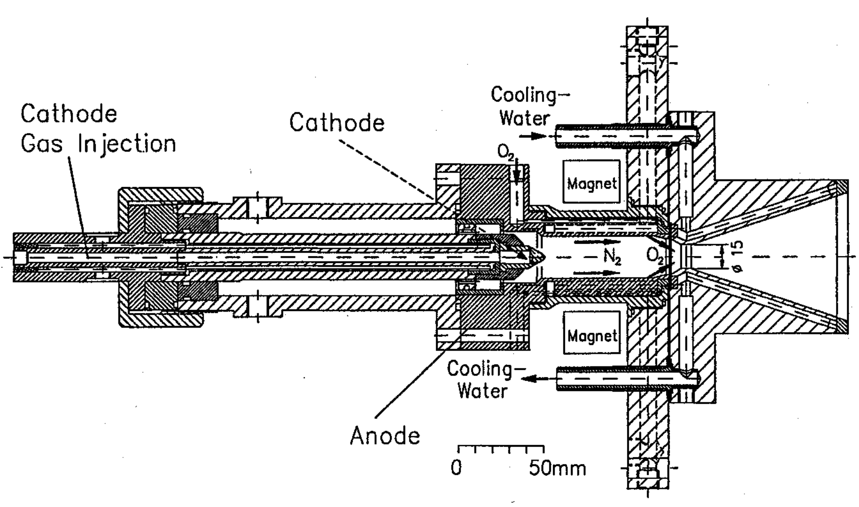

Fig. 14 Thermal plasma generator RB2.

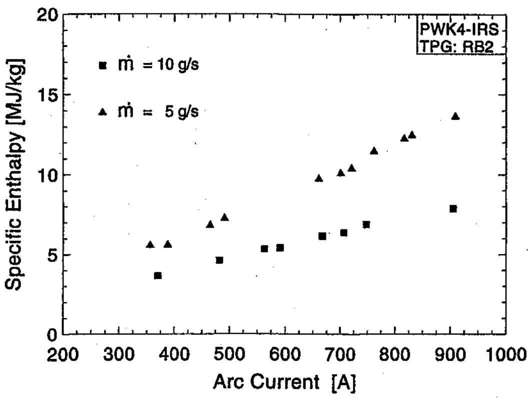

Fig. 15 Average specific enthalpy at nozzle exit as a function of the arc current for RB2.

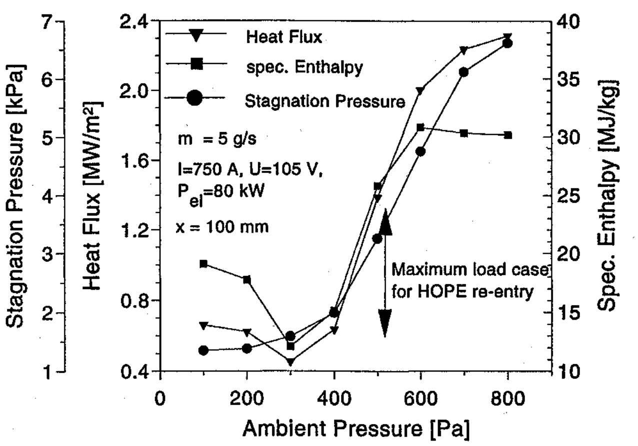

Fig. 16 Local specific enthalpy, heat flux, and stagnation pressure as a function of the ambient pressure for a mass flow rate of 5 g/s.

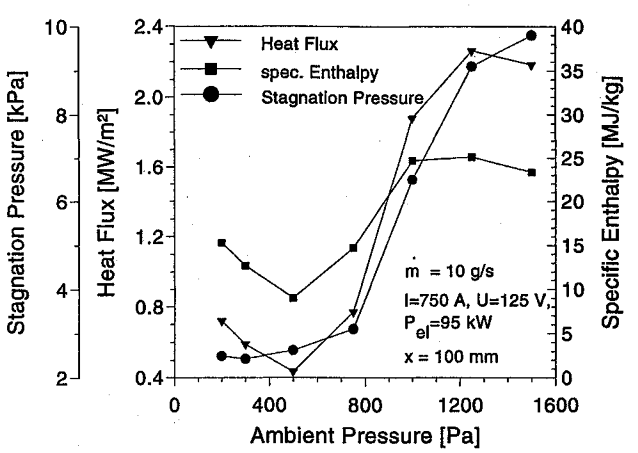

Fig. 17 Local specific enthalpy, heat flux, and stagnation pressure as a function of the ambient pressure for a mass flow rate of 10 g/s.

space plane Hope can be simulated. By increasing the mass flow rate to 10 g/s (Fig. 17) and slightly increasing the ambient pressure, the stagnation pressure reaches about 10 kPa at a heat flux level of ~2.2 MW/m^2 and a specific enthalpy of 24 MJ/kg, respectively. To meet the requirements of Colibri, the stagnation pressure has to be increased again by a factor of 2, which can easily be done by further increasing the mass flow rate and ambient pressure.

Erosion Behavior

For the investigation of ceramic TPS materials of modern re-entry vehicles, chemically pure high enthalpy airflows are required so as to not influence the catalytic and erosive behavior. In contrast to the inductively heated generator IPG, where the plasma is not in contact with metallic electrodes, erosion of the electrodes cannot be completely avoided in arc-heated devices (MPG and TPG).

Different kinds of erosion products may contaminate the plasma flow created by TPGs and MPGs. In principle, in TPGs operated with cold copper cathodes (Huels-arc and constricted arc heaters), the arc attachment on the cathode is spotty. It is possible to reduce, but not to eliminate, copper erosion by applying magnetic fields that swirl around the arc foot on the electrode and by injecting a protection gas flow in the electrode region.[3]

Since copper is nearly fully catalytic for atomic nitrogen and oxygen, for catalycity investigations copper contamination has to be avoided. For this reason all arc heated devices in our studies are operated with hot cathodes made of 2%-thoriated tungsten, which means that the electron emission is thermionic and the cathode erosion is lowered to the level of sublimation.[40] In Fig. 18 the impurity levels within the MPG and TPG wind tunnels at the IRS are compared to those equipped with Huels-arc heaters and constricted arc heaters. As described in the sections above copper erosion from the anode can be avoided completely by additional protection gas injection and by applying an axial magnetic field in case of the TPG-RB2.

In addition to the importance of the absolute quantity of eroded material in the jet, the influence of different materials on the materials tests has to be considered. For example, copper particles ejected from arc spots are found to be partly deposited on the material samples and influence the catalytic behavior of the materials samples tested in facilities equipped with TPGs.

Tungsten, however, eroded from MPG cathodes reacts with the oxygen within the air. Since tungsten oxides are volatile at the high temperatures of the material samples, tungsten deposits have never been detected on material samples tested in the IRS wind tunnels. But even the tiny cathode erosion, which is about equal to the sublimation rate, may also substantially influence the catalytic behavior of TPS materials or heat flux probes under heat load. To clarify the uncertainties about this influence on the surface catalycity, heat flux measurements within the MPG tunnel PWK2, and the electrodeless inductively heated PWK3 have been conducted and compared. For these tests, heat flux probes manufactured with different materials were used to determine the dependency of the heat transfer rate on the material type. The heat transfer rates as a

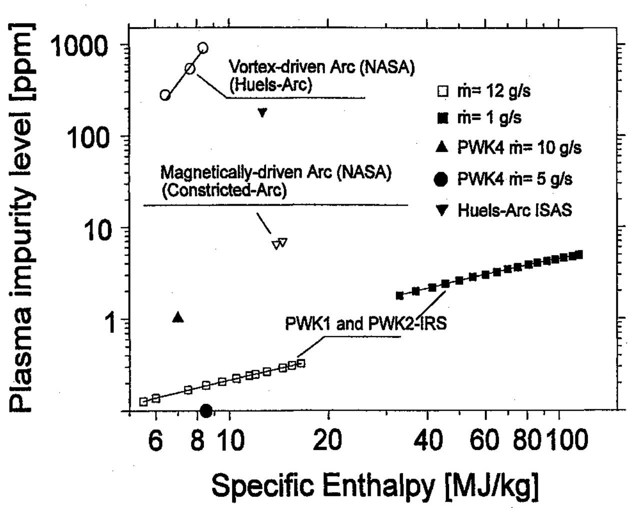

Fig. 18 Erosion rates in plasma generators (partly from Refs. 7 and 44).

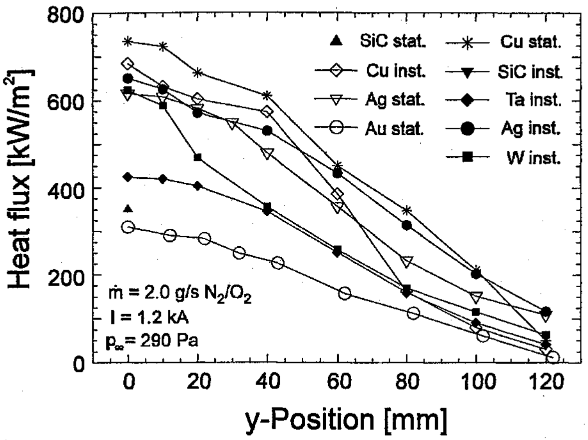

Fig. 19 Heat fluxes within the PWK2 under peak heating conditions for Hermes leading edge (Fig. 1) as a function of the radial probe position measured with stationary (stat.) and transient (inst.) probes of different materials.

function of the radial probe position within the PWK2 are shown in Fig. 19. The very high catalycity of copper compared to gold can clearly be seen. The heat flux ratio $\dot{q}_{Cu}/\dot{q}_{Au}$ under Hermes peak heating conditions within PWK2 is approximately 2.5. Measurements within PWK3 under similar conditions show the same heat flux ratio. This result showed that the heat flux measurements performed in PWK2 are not influenced by cathode erosion products, and therefore, qualify the MPG tunnels PWK1 and PWK2 for catalycity investigations. Since the erosion rates of the TPG-RB2 are of the same qualitative magnitude as in the MPG (see Fig. 18), this is also true for the TPG tunnel PWK3.

Summary

Four medium-size plasma wind tunnels have been built up at the Institut für Raumfahrtsysteme. They are equipped with different plasma sources: MPD devices, a thermal arcjet generator, and an inductively heated accelerator. With these facilities the most important parts of the trajectories of small space planes, capsules, and space probes can be simulated adequately with respect to the qualification of the TPS systems. Furthermore, these plasma wind tunnels are excellent tools for the validation of aerothermodynamic codes creating reacting high-enthalpy gas flows close to the plasma source, which are in neither chemical nor thermal equilibrium. A wide range of measurement techniques have been qualified and are available for detailed characterization of the re-entry simulation plasma. For all wind tunnels, the quality of the high-enthalpy gas is very good in terms of purity, which makes them reliable instruments for the investigation of erosive and catalytic behavior of TPS materials.

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