SACOMAR

Technologies for Safe and Controlled Martian Entry

SPA.2010.3.2-04

EU-Russia Cooperation for Strengthening Space Foundations (SICA)

Re-entry Technologies and Tools

Theme 9 - Space
Activity 9.3 - Cross-Cutting-Activities
Area 9.3.2 - International Cooperation

Deliverable Reference Number: D 5.1
Deliverable Title:

Test Plan for Experiments

Due date of deliverable: 21st April 2011

Actual submission date: 30th June 2011

Start date of project: 20th January 2011

Duration: 18 months

Organisation name of lead contractor for this deliverable: DLR, AS-HY

Revision #: 0

Project co-funded by the European Commission within the seventh Framework Programme		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission	
RE	Restricted to a group specified by the consortium (including the Commission	
CO	Confidential, only for members of the consortium (including the Commission Services)	

APPROVAL

Title	**issue**	revision
Test Plan for Experiments	1	0

Author(s)	**date**
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Approved by	**date**
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Nomenclature

Abbreviations

CFD	Computational Fluid Dynamics
DLAS	Diode Laser Absorption Spectroscopy
DLR	German Aerospace Center
DSMC	Direct Simulation Monte Carlo Method
HEG	DLR's High Enthalpy Shock Tunnel Göttingen
HFM	Heat Flux Microsensor
ICP	Inductively Coupled Plasma
IPM	Institute for Problems in Mechanics
IR	Infrared
ITAM	Institute of Theoretical and Applied Mechanics
L2K	DLR's 1.4 MW arc heated facility in Cologne
LIF	Laser Induced Fluorescence
TPS	Thermal Protection System
TsAGI	Central Aerohydrodynamic Institute
TsniiMash	Central Research Institute of Machine Building
WP	Work Package

Symbols

D	Diameter
h	Enthalpy
Ma	Mach number
p	Pressure
r	Radius
Re	Reynolds number
T	Temperature
u	Flow velocity
x	Axial position
ρ	Density
φ	Orientation angle

Subscripts

e	edge
ini	initial
t	total
∞	free stream

1 Executive summary

1.1 Scope of the deliverable

With the SACOMAR project a better understanding of the physico-chemical phenomena that dominate the aerothermodynamic problems during Martian entry shall be achieved by a combined experimental and numerical approach. For the experimental activities five high enthalpy facilities, each of them with a long-term experience in measurements related to aerothermodynamic problems, will be used. The set of facilities includes long duration as well as short duration facilities. Long duration facilities are arc heated facilities and inductively coupled plasma generators. Both types of facilities are well instrumented and have widely been used for TPS testing. The short duration high enthalpy facilities include a shock tunnel and a hot shot facility. With their higher Reynolds numbers they allow to study non-equilibrium relaxation phenomena behind the shock at flight relevant conditions.

Compared to Earth atmosphere less experience has been accumulated on thermochemical modelling of Martian atmosphere during the past decades. Nevertheless, Mars-related thermochemistry is more complex and covers a wider range of thermodynamical states due to the following aspects:

- The main species in Martian atmosphere is CO_2, which is a polyatomic species. There are models that describe the thermochemical behaviour of polyatomic models, but the degree of validation of these models is poorer compared to atomic or diatomic species.
- The surface pressure level of the Martian atmosphere is below 1000 Pa. Therefore, chemical reactions as dissociation and ionisation are initiated at lower temperatures.
- Due to the lower density of the Martian atmosphere compared to Earth thermal and chemical freezing is to be expected, which has a significant influence on surface chemistry and heat flux rates.

In this document all participating facilities are described with particular focus set to experiences and testing capabilities in Martian atmosphere. Based on the operating parameters the main specifications for the experimental activities are derived. A common specification for all facilities is required in order to achieve optimal coordination of experimental activities. The necessities of future missions to Mars are exemplarily included by taking reference to trajectory points of the EXOMARS mission.

Finally, particular specifications are defined for each of the five test facilities. The specifications are based on the operational regimes and experimental capabilities of the individual facilities.

1.2 Results

The characteristic properties of the participating facilities allow to cover all three important thermochemical regimes, i.e. equilibrium, non-equilibrium and frozen chemistry:

- In the plasmatron facilities U-13 and IPG-4 the flow is very close to thermochemical equilibrium, but subsonic.
- The flow in the two short duration facilities HEG and IT-2 is hypersonic and in thermochemical non-equilibrium.
- The arc heated facility L2K provides a hypersonic thermochemically frozen flow enqironment.

With reference to the EXOMARS trajectory four test conditions could be identified which enable direct facility-to-facility comparison

- at identical total enthalpy conditions in the reservoir,
- at comparable free stream enthalpies in different thermochemical regimes.

The model geometry was chosen to be a flat-faced cylinder geometry with rounded edges. This geometry

- is a good representation of the windward surface of a capsule,
- provides largest possible shock stand-off distance in hypersonic flow maximizing the experimental possibilities of probing gas properties in the shock layer, and
- does not introduce additional complexity to numerical simulation.

Due to individual constraints, which either arise from facility size or from measurement techniques, a fully identical test geometry cannot be used in all facilities. For the plasmatron facilities the cylinder's diameter will be D = 50 mm and the edge radius r_e = 11.5 mm, for the short duration facilities the diameter will be D = 100 mm with the same edge radius. In the arc heated facility L2K both diameters will be tested.

Finally, a test matrix was defined specifying test conditions in terms of total enthalpy and Pitot pressure for each test facility. Based on the experiences and capabilities of the facilities, measurement techniques were specified to be applied for

- heat flux measurements and
- characterization of the free stream.

1.3 Specific highlights

Not applicable

1.4 Forms of integration within the work package and with other WPs

The test plan given in this document bases on the general requirements which were evaluated in task 4.1 op WP 4. It is the central document of task 5.1 in WP 5. In addition, it provides fundamental information for all other tasks in WP 5 by specifying test conditions, model geometry and measurement techniques for the test campaign in the five participating high enthalpy ground test facilities.

Model geometry and test conditions are also input parameters for the tasks in WP 7 where a CFD simulation of the experiments will be performed.

1.5 Problem areas

Not applicable

2 Introduction

A fundamental prerequisite for reliable application of CFD simulation to hypersonic planetary entry flows is a realistic thermochemical model of the planet's atmosphere. Although computational power has grown by orders of magnitudes within the last years, a CFD simulation code that is applicable to 3D configurations is still far away from being able to account for all microscopic effects that have influence on the macroscopic behaviour of a gas at high temperatures. The transfer from microscopic to macroscopic scale is performed by thermochemical modelling. Therefore, in advance to a CFD validation a reliable validation of the implemented thermochemical model has to be performed.

With regard to Earth atmosphere there is a huge experience accumulated and there has been a large number of space missions as well as flight and ground experiments that can be used for model validation. Compared to Earth atmosphere the thermochemical modelling of Martian atmosphere is more complex and covers a wider range of thermodynamical states due to several aspects:

- The main species in Martian atmosphere is CO_2, which is a polyatomic species. There are models that describe the thermodynamical behaviour of polyatomic models, but the degree of validation of these models is less compared to atomic or diatomic species.
- The surface pressure level of the Martian atmosphere is below 1000 Pa. Therefore, chemical reactions as dissociation and ionisation are initiated at lower temperatures.
- Due to the lower density of the Martian atmosphere compared to Earth thermal and chemical freezing is to be expected, which has a significant influence on surface chemistry and heat flux rates.

The main objectives of the SACOMAR study are the improvement of experimental and numerical tools to study the aerothermodynamic problems of Martian entry, the achievement of a better understanding of physical phenomena and the creation of a data base. As experimental tools all three types of high enthalpy facilities, which are used for the measurement of aerothermodynamic properties and qualification of TPS materials, will be used. Long duration facilities are arc heated facilities and inductively coupled plasma generators. Both types of facilities are well instrumented and have been widely used for TPS testing. The short duration high enthalpy facilities operate at higher Reynolds numbers and allow to study thermochemical relaxation phenomena behind the bow shock at flight relevant conditions.

In this document the participating test facilities are described in detail, with particular focus to the main objectives of SACOMAR. Furthermore, the experimental setup and the test conditions for the experimental activities within SACOMAR will be specified. Specifications will be based on the operational regimes of the individual facilities and the necessities of future missions to Mars which are exemplarily deduced from the EXOMARS mission.

3 Facilities

The experimental work within the SACOMAR project will be performed in five high enthalpy ground test facilities, each of them having a long-term experience on experimental investigation of aero-thermodynamic problems and some of them on qualification of TPS materials as well. To cover all relevant thermochemical regimes the set of facilities includes all three different types of high enthalpy facilities:

- long duration inductively heated facilities with subsonic flow,
- long duration arc jet facilities with hypersonic flow,
- short duration facilities with hypersonic flow.

Generally the long duration facilities, i.e. plasmatrons and arc heated facilties, are used for TPS testing and qualification. Based on the long duration capability the thermal interaction between flow field and thermal protection materials can be investigated in these facilities at all relevant temperature levels. In the short duration high enthalpy facilities higher Reynolds numbers can be achieved which allow to study thermochemical relaxation phenomena behind the bow shock at flight relevant conditions.

In the following subsections characteristic features of the individual facilities will be described in more detail, starting with the long duration facilities in sections 3.1 to 3.3. A description of the short duration test facilities will follow in sections 3.4 and 3.5.

3.1 Plasmatron facility U-13 (TsniiMash)

U-13 is a plasmatron facility at TsniiMash with a 1000 kW inductively coupled plasma (ICP) heater. A principal sketch as well as a photograph of the facility are shown in Fig. 1.

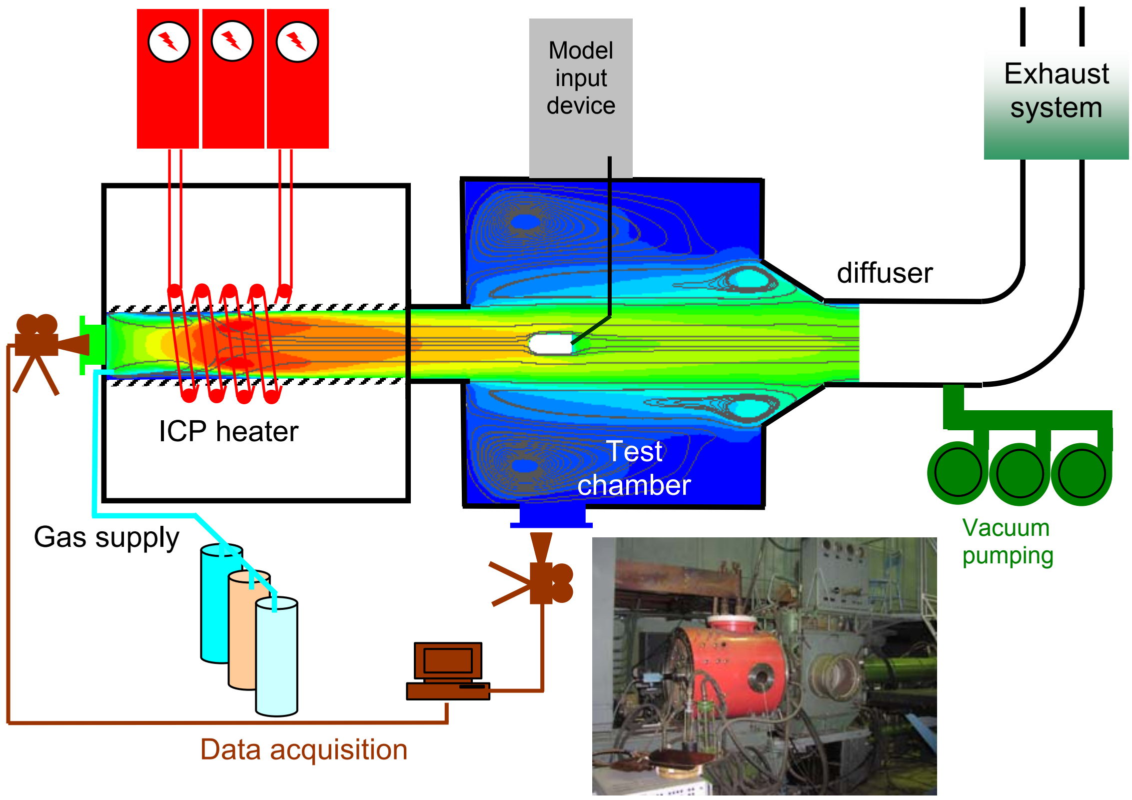


Fig. 1: Principal sketch and photograph of the plasmatron facility U-13 at TsniiMash.

The power supply which operates at 440 kHz allows to achieve total enthalpies between 5 and 30 MJ/kg in the test chamber. On stagnation point models heat fluxes in the range of 10-5000 kW/m^2 can be achieved at stagnation pressures between 5 and 200 hPa. Thus, the facility is enabled to reproduce flight heat transfer conditions (pressure, enthalpy, chemical species) on tested models which are representative for entering planetary atmospheres. Usually atmospheric air is used as working gas, but there is also possibility and experience to use other working gases, e.g. nitrogen, argon, and CO_2, to simulate entry in atmospheres of the other planets [1]. An impression on the flow field appearance is given in Fig. 2.

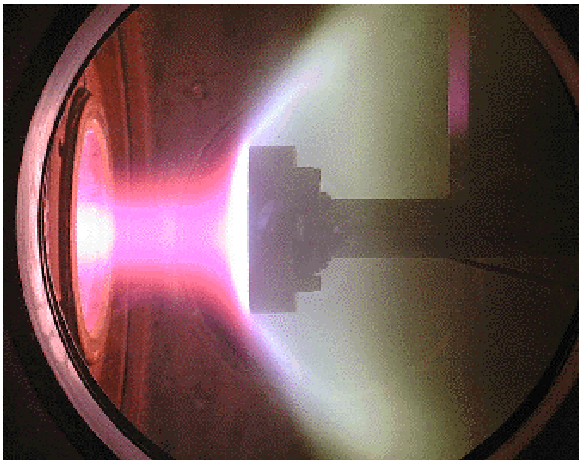


Fig. 2: Plasma flow around a model in U-13.

Since getting operational in 1982 the U13-HFP facility has intensively been used for different tasks related to aerothermodynamics and TPS characterization, as e.g. heat transfer in high enthalpy gas flows, surface catalycity of TPS, TPS life-cycle tests, thermal resistance of anti-oxidation coatings, TPS aging, radiophysical properties of plasma flow, magnetic field effects on plasma flow [1-8]. In addition, the facility was used for the development of plasma flow diagnostics tools.

Intrusive and non-intrusive techniques are available for diagnostics and flow characterization. Sensor-based measurement include heat fluxes and Pitot pressures. Available non-intrusive techniques are emission spectroscopy, pyrometry, IR-thermography and microwave interferometry.

3.2 Plasmatron facility IPG-4 (IPM)

IPG-4 is a 100 kW plasmatron facility at the Institute for Problems in Mechanics (IPM) of the Russian Academy of Sciences. The facility can be operated in both, subsonic and supersonic mode. The power supply operates at a frequency of 1.76 MHz heating the working gas in the plasma torch which has a diameter of 80 mm and a length of 400 mm. Operational experience has been gained with several working gases, i.e. air, CO_2, nitrogen, oxygen, and argon. A photograph of the facility is shown in Fig. 3.

In subsonic mode, IPG-4 can produce high enthalpies in the range of 10-40 MJ/kg at working chamber pressures of 10-1000 hPa in air and nitrogen and 10-300 hPa in CO_2 flows. Excellent stability and reproducibility of operation regimes have been achieved. Fig. 4 gives an impression on the typical flow field appearance in subsonic CO_2 flow.

Fig. 3: Plasmatron facility IPG-4 at IPM.

Fig. 4: CO_2 flow around a TPS sample in IPG-4.

The methodology of extrapolation of stagnation point heat transfer from Plasmatron ground data to flight conditions has already been developed at IPM [9-17]. IPG-4 has intensively been used during the ISTC, INTAS-ESA and INTAS/CNES projects to

- characterize the operational behaviour in comparison to other plasmatron facilities,
- study stagnation point heating on hot and cold walls, and
- to determine catalytic properties of ceramic TPS materials in dissociated air and carbon dioxide flows.

Several sensor-based and non-intrusive measurement techniques are available. Different calorimeters are used for measurements of stagnation point heat fluxes. Dynamic and Pitot pressures are measured by sensors. Non-intrusive techniques include emission spectroscopy and pyrometry.

3.3 Arc heated facility L2K (DLR)

L2K is one of the two test legs of DLR's arc heated facilities LBK which have been playing an important role in the qualification and testing of TPS components and materials in the frames of several European and German programmes, as e.g. Hermes, MSTP, ALSCAP, X-38, ASTRA, etc. Additional activities like tests on the HYFLEX tile model, the ablator material of the USERS capsule, some preparatory activities for the MARS PREMIER programme, etc. allowed the LBK team to gain more experience in aerothermodynamics and qualification of TPS-components for different planetary entry conditions.

A sketch of LBK is shown in Fig. 5. The L2K test leg is equipped with a Huels type arc heater with a maximum electrical power of 1.4 MW that is used to transfer the working gas to a high enthalpy state. At its downstream end the arc heater is connected to a convergent-divergent nozzle which accelerates the gas to hypersonic velocities. After passing the nozzle exit the accelerated gas enters the test chamber where it forms a free jet. Depending on the nozzle setup Mach numbers between 4 and 8 at Reynolds numbers up to 10000/m can be achieved. Models can be exposed to cold wall heat flux rates up to 4 MW/m^2 at stagnation pressures up to 250 hPa. A more detailed description of the facility can be found in [18,19].

One of the main advantages of the L2K arc heater is its robustness. Although for many aerospace applications air is used as a working gas, L2K can easily be operated with other gases as well. Argon, Nitrogen and Carbon dioxide have intensively been used during the recent years [20,21]. Components for storage and supply of those gases are permanently available. For simulation of Martian atmosphere L2K is operated with a gaseous mixture consisting of 97% carbon dioxide and 3% nitrogen.

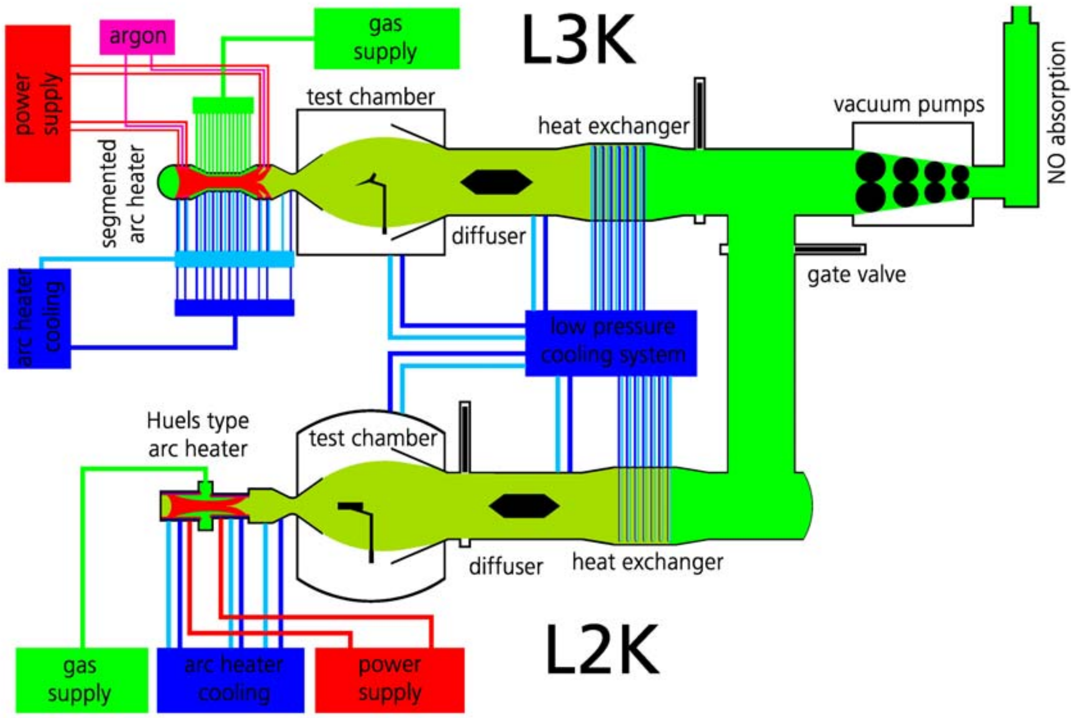


Fig. 5: Sketch of the LBK facility

The huge test chamber of L2K is equipped with several windows allowing for the application of non-intrusive diagnostic tools, in particular optical diagnostic techniques for the characterisation of high enthalpy flow fields [22,23,24]. Emission spectroscopy, absorption spectroscopy, diode laser spectroscopy and laser induced fluorescence spectroscopy on NO and two-photon laser induced fluorescence on oxygen atoms can be applied providing valuable information on the flow properties. Rotational and vibrational temperatures, densities, flow velocities, and shock stand-off distances can be measured. The techniques are permanently available and continuously used at LBK. Complementary to the spectroscopic tools intrusive techniques are applied to measure cold wall heat flux rates and Pitot pressure profiles [25,26].

3.4 High enthalpy shock tunnel HEG (DLR)

The High Enthalpy Shock Tunnel Göttingen (HEG) of the German Aerospace Center (DLR) is one of the major European hypersonic test facilities. It was commissioned for use in 1991 and was utilised since then extensively in a large number of national and international space and hypersonic flight projects. Originally, the facility was designed for the investigation of the influence of high temperature effects such as chemical and thermal relaxation on the aerothermodynamics of entry or re-entry space vehicles. HEG is a free piston driven shock tunnel [27,28] and was developed and constructed in the framework of the European HERMES program over the period 1989–1991. When becoming operational in 1991, it was the largest facility of its type worldwide at that time. A schematic of HEG is given in Fig. 6.

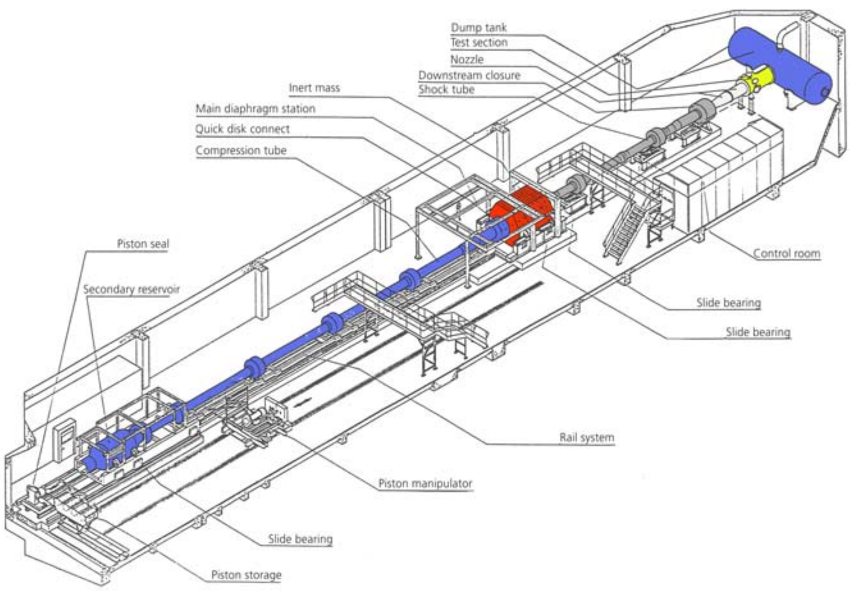


Fig. 6: Schematic of the High Enthalpy Shock Tunnel Göttingen (HEG).

The facility's overall length is 62 m and it weighs 280 t. Approximately a third of its weight is contributed by an inert mass which is used to reduce the tunnel recoil motion. The compression tube is closed by a hydraulic oil system at the main diaphragm station. The shock tube is connected to the nozzle of the tunnel at the downstream closure, which is also driven by oil hydraulics to close and seal the tunnel. The compression tube has a length of 33 m and a diameter of 0.55 m. The shock tube is 17 m long with a diameter of 0.15 m. HEG was designed to provide a pulse of gas to a hypersonic convergent-divergent nozzle at stagnation pressures of up to 200 MPa, and stagnation enthalpies of up to 23 MJ/kg. Regarding the test gas, no basic limitations exist. Fully characterized operating conditions exist for air, nitrogen and carbon dioxide.

Over the last years the HEG operating range was subsequently extended. Low enthalpy conditions were included to generate test section conditions which allow investigating the air flow past hypersonic flight configurations from Mach 6 at low altitudes up to Mach 10 in approximately 33 km altitude. Other conditions duplicate M = 7.4 flight conditions in 28 km and 33 km, and were used for the ground based testing of the HyShot II [29] and IV supersonic combustion flight experiment configurations. For the high enthalpy conditions the testing time is about 1 ms. For the low enthalpy conditions, the test time ranges from 3 – 6 ms. Additional in information about HEG is given in [30].

For tests in Martian atmosphere two test conditions have been included in the set of standard test conditions. The main parameters of these test conditions are listed in Table 1.

Table 1: CO_2 test conditions of HEG

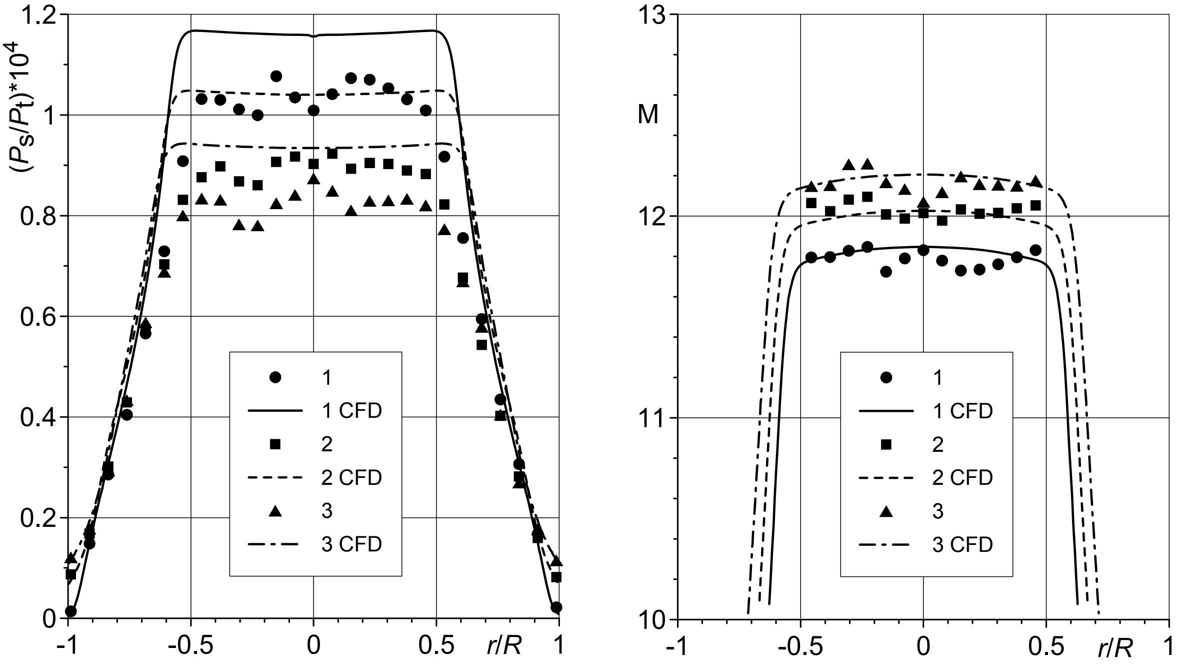
Condition	IVI	IVII
Gas	CO_2	CO_2
p_0 [MPa]	84	6.2
T_0 [K]	5900	3800
h_0 [MJ/kg]	15	8.1
Ma_∞ [-]	6.6	6.9
p_∞ [Pa]	2400	150
T_∞ [Pa]	1500	727
ρ_∞ [kg/m^3]	6.5	0.9
u_∞ [m/s]	4400	3200
Re_m [10^6/m]	0.53	0.09

3.5 Hot-shot wind tunnel IT-2 (TsAGI)

The hot-shot wind tunnel IT-2 is a short duration impulse facility at TsAGI [31-33]. High values of total pressure P_0 and total temperature T_0 are achieved in a small chamber filled with the test gas by electrical discharge. Usually, nitrogen and carbon dioxide are used as test gases. After diaphragm rupture, the test gas flows through a conical or profiled nozzle into the evacuated tank. The nozzle diameter can be varied in several stages between 44 cm and 90 cm. For about 100 ms the flow can be assumed as quasi-stationary. The total pressure can be varied in the range of 120-1500 bar with a total temperature between 1500 K and 5000 K. During a test run, total pressure and total temperature decrease.

In the test section Mach numbers up to M = 12 can be obtained in CO_2 flow, in nitrogen flow the maximal achievable Mach number is 20. For the standard CO_2 conditions with a total pressure of 350 bars and a total temperature of 1700 K the free stream has already been characterized in previous test campaigns. Lateral profiles of relative stagnation pressure and Mach number are plotted in Fig. 7. The numbers indicate different distances from the nozzle exit area, i.e. x = 10 mm (index 1), x = 200 mm (index 2), and x = 400 (index 3). The experimental data which are given as points are compared to the results of a numerical simulation (lines). The corresponding heat flux profiles are shown in Fig. 8 with the corresponding Fay-Riddell value taken as reference heat flux q_{ref}.

On models heat fluxes and pressures can be measured at various locations. Non-intrusive techniques include Schlieren and shadow visualization of the flow as well as electron concentration measurements close to the model surface.



(a) relative stagnation pressure (b) Mach number

Fig. 7: Lateral profiles in IT-2 at Ma = 12 (CO_2 standard conditions).

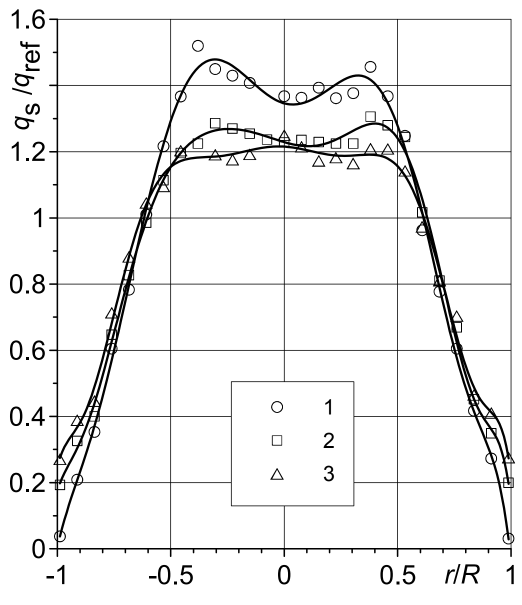


Fig. 8: Lateral heat flux profiles in IT-2 at Ma = 12 (CO_2 standard conditions).

4 Model geometry

Gas-phase chemistry in Martian atmosphere and its influence on heat fluxes is a topic that itself is dominated by complex physico-chemical phenomena. Therefore, the geometry of the model that is used for heat flux evaluation should not introduce major additional complexity. It should be kept as simple as possible to enable best possible link between heat flux measurements on one side and the measured free stream properties as well as modelling parameters and correlated numerical results on the other side.

Vehicles that are supposed to enter Martian atmosphere are designed as blunt bodies which in an hypersonic flow field cause the formation of a strong bow shock on the front side generating substantial heating of the gas and subsequently of the vehicle as shown in the sketch in Fig. 9.

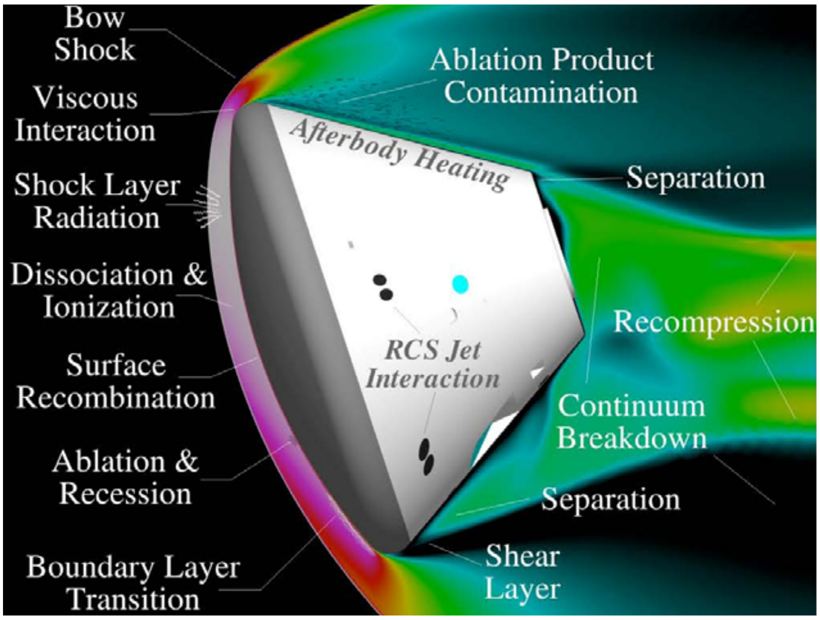


Fig. 9: Sketch of the atmospheric entry scenario of a capsule.

Of course, the test configuration should reflect this scenario. A well-suited simplification of a capsule-like geometry is a flat-faced cylinder. Its principal geometry is sketched in Fig. 10. The photograph in Fig. 11 demonstrates that the flow topology is similar to the front part of a capsule. The contour of the bow shock is clearly visible, separating the free stream from the intensively glowing heated gas in the shock layer. Compared to other blunt geometries, a flat-faced cylinder provides the largest possible shock stand-off distance for the hypersonic test facilities (HEG, IT-2 and L2K). By that, it maximizes the experimental possibilities of probing the gas properties in the shock layer. The flat-faced cylinder geometry will be used for all facility tests. To avoid grid related problems related to sharp edges during numerical simulation the edge of the cylinder should be rounded (see Figure 1).

Due to individual constraints, which either arise from facility size or from measurement techniques, a fully identical test geometry cannot be used in all facilities. For the plasmatron facilities the cylinder's diameter will be D = 50 mm and the edge radius r_e = 11.5 mm. This corresponds to the so-called "standard ESA geometry" which had been established about 25 years ago. At almost all long duration high enthalpy facilities corresponding models and model holders are available which keeps the manufacturing necessities for the SACOMAR test programme small and provides good chances for an easy comparison to already existing data from different atmospheres.

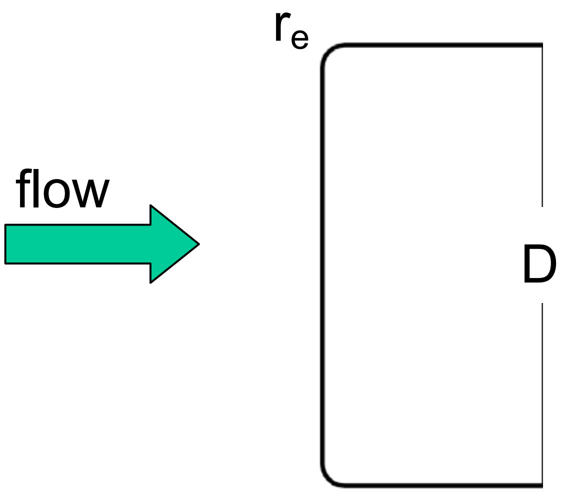


Fig. 10: Model geometry.

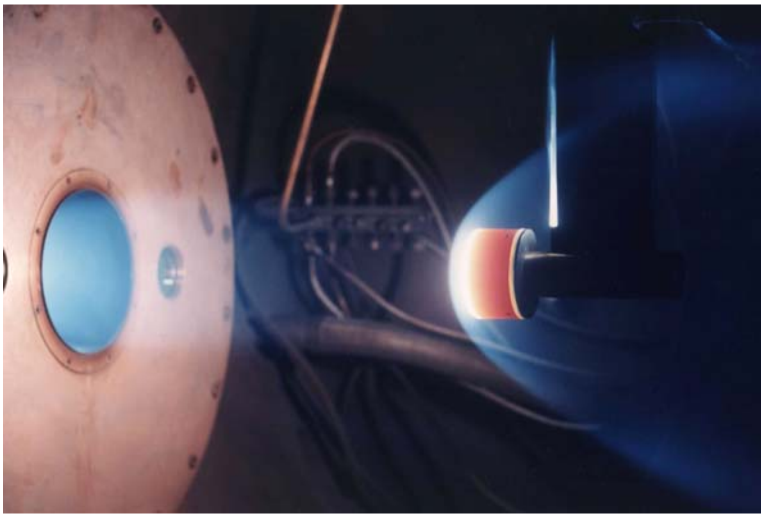


Fig. 11: Flat-faced cylinder model in hypersonic flow.

For the short duration facilities HEG and IT-2 a 50 mm cylinder is supposed to be too small to embed all necessary instrumentation. Therefore, a flat-faced cylinder with a diameter D = 100 mm is foreseen for measurements in HEG and IT-2. The edge radius should be identical to the smaller cylinder, i.e. r_e = 11.5 mm.

In the L2K facility tests will be performed on both cylinder geometries. These tests are supposed to identify size effects and provide a bridge between the measurement in short duration hypersonic and the long duration subsonic ground test facilities.

5 Test conditions

The definition of test conditions is based the general requirements for the SACOMAR study which have been evaluated in WP 4 [34]. The test conditions are based on characteristic points of the EXOMARS entry trajectory. These trajectory points are listed in Table 2. They cover almost the complete entry phase from high enthalpy conditions at nearly interplanetary cruise speed to low enthalpy conditions at low altitude.

Table 2: EXOMARS trajectory points

trajectory point	entry time	velocity	enthalpy	Pitot pressure
	[s]	[m/s]	[MJ/kg]	[hPa]
1	81	5228	13.8	55
2	104	4072	8.5	82
3	113	3581	6.6	82
4	120	3266	5.5	79
5	131	2691	3.8	70
6	140	2317	2.9	62

The main objectives of the SACOMAR study do not require that test conditions fully duplicate one of the trajectory points. Appropriate test conditions have to reproduce important thermochemical phenomena and should be achievable in a complementary manner in the test facilities. Therefore, test conditions are supposed to be appropriate if

- they are sufficiently close to one or two trajectory points, and
- take into account the individual capabilities of the test facilities, and
- consider the characteristics the flow field properties in terms of thermochemistry.

Based on these considerations four different enthalpy levels have been defined for testing. The details are listed in Table 3. The highest enthalpy level is directly related to trajectory point 1, the other three enthalpy levels are close to trajectory points 2, 4, and 6, resp.

Table 3: SACOMAR test conditions

Test condition	enthalpy
	[MJ/kg]
FC-1	13.8
FC-2	9.0
FC-3	5.5
FC-4	2.0

The test conditions refer to a representative Martian mixture which is composed of 97% carbon dioxide and 3% nitrogen.

At this stage Pitot pressures are intentionally not included in the test conditions. The reason behind is that thermochemical behaviour changes with pressure level. Therefore, Pitot pressure can be regarded as test parameter in facilities which are able to set total enthalpy and Pitot pressure in-dependently (plasmatron and arc heated facilities). By varying the Pitot pressure between 10 hPa and 80 hPa in these facilities, a much larger experimental database will be generated allowing for better identification of thermochemical phenomena and providing a broader reference dataset for the validation of thermochemical models with numerical simulations. For the short duration facilities the Pitot pressure is more or less fixed for a certain operating condition. Therefore, a systematic variation of Pitot pressure is not intended for these facilities.

6 Test Matrix

From the considerations in the preceding sections concerning test conditions and model definitions the test matrix has been derived. It listed in Table 4. It contains the test conditions in terms of enthalpy and Pitot pressure for each test facility. As mentioned above, several Pitot pressures between 10 and 80 hPa will be applied in the plasmatron facilities and in L2K. Since at L2K two model sizes will be tested, only two different pressure levels will be considered there. At the highest enthalpy level, i.e. test condition FC-1, additional measurements will be performed as reference to the DSMC computation to be performed in WP 7 by ITAM.

Table 4: SACOMAR test matrix

Test facility	Test condition	enthalpy	Pitot pressure	model diameter
		[MJ/kg]	[hPa]	[mm]
U-13	FC-1	13.8	80,40,20,10	50
	FC-2	9.0	80,40,20,10	50
IPG-4	FC-1	13.8	80,40	50
	FC-2	9.0	80,40	50
L2K	FC-1	13.8	80,20,10	50,100
	FC-2	9.0	80,20	50,100
HEG	FC-1	13.8	700	100
	FC-2	9.0	80	100
IT-2	FC-4	2.0	tbc	100
	FC-3	5.0	tbc	100

The enthalpy values listed in the table correspond to the total enthalpy in the reservoir of the facility. For the plasmatron facilities this enthalpy value is identical to the total enthalpy in the free stream close to the model's surface, as long as these facilities are operated in subsonic mode.

For the hypersonic facilities, i.e. HEG, IT-2, and L2K, the reservoir enthalpy is supposed to be different from the enthalpy in the free stream due to thermochemical relaxation processes which take place along the nozzle flow and cause non-equilibrium or frozen conditions in the free stream. The particular choice of the SACOMAR test conditions allows to investigate influences of the non-equilibrium state of the free stream on surface heating as well.

As an example, HEG testing at test condition FC-1 is considered. For this condition a free stream velocity of about 4400 m/s is expected corresponding to Table 1. In hypersonic flow, the total enthalpy can roughly be determined from the kinetic energy of the free stream. For the expected velocity, it corresponds to 9.7 MJ/kg which is close to the enthalpy of test condition FC-2. By comparing the measured data to plasmatron test at FC-2, the influence of partial non-equilibrium on surface heating can be determined.

In a similar way, an enthalpy of 4.5 MJ/kg results for the free stream in L2K from an expected free stream velocity of 3000 m/s at test condition FC-1. This enthalpy value fairly well corresponds to the total reservoir enthalpy of test condition FC-3. In addition it is close to the total enthalpy of the free stream in HEG at condition FC-2 which results to 5.1 MJ/kg from an expected free stream velocity of 3200 m/s. So, the chosen test conditions provide several links between equilibrium flow in the plasmatron facilities, non-equilibrium flow in the short-duration facilities HEG and IT-2 and frozen flow in the arc heated facility L2K.

7 Measurements

The main objective of all experimental activities in SACOMAR is to provide reliable measured reference data for the validation of thermochemical models of Martian atmosphere and their application within numerical simulation tools. Principal focus is set to a better understanding of thermochemical relaxation phenomena and its influence on surface heating.

The set of required measurements can be divided into three different subsets:

(1) measurements to characterize the test condition,

(2) heat flux measurements at the stagnation point of the model,

(3) auxiliary measurements that characterize the free stream properties and - in case hypersonic flow – the properties inside the shock layer.

Compliance to the test conditions will generally be demonstrated by measurements of the reservoir pressure. In the long-duration facilities the total enthalpy in the reservoir can then be determined from an additional measurement of the mass flow rate of the working gas. In the short-duration facilities the enthalpy is derived based on the measured reservoir pressure from the thermodynamics of the heating process.

At model location compliance to the test matrix will be demonstrated by Pitot pressure measurements. In addition to a single measurement on the axis of the flow field which is the minimal requirement a measured radial Pitot pressure profile would provide a huge benefit for numerical simulation, since it allows a more realistic prescription of the flow properties at the inflow boundary of a model computation.

Heat flux measurements are performed to demonstrate the influence of surface catalycity. A variation of the surface material will systematically be done in the long-duration test facilities, i.e. plasmatron facilities and arc-heated facility. The set of surface material will include the two extreme cases, i.e.

- a fully catalytic wall and
- a non-catalytic wall.

For Martian atmosphere silver is supposed to be a fully catalytic surface material and quartz is supposed to be non-catalytic. In addition to the fully catalytic and non-catalytic cases at least one technical surface material with intermediate catalycity, e.g. copper or stainless steel, will be investigated as well. Copper will be included in all three long-duration facilities, stainless steel in IPG-4 and L2K.

Calorimeters will be used for heat flux measurement in the plasmatron and arc heated facilities, either slug calorimeters or water-cooled devices. In addition, a commercial heat flux microsensor (HFM) will be applied in L2K for confirmation of the absolute level of heat flux measurement.

In HEG, calorimetric heat flux measurements are not possible due to the short test duration. Heat flux rates are deduced here from temperature measurements using thermocouples which are integrated into the model surface.

The auxiliary measurements shall provide measured information about the free stream. These data, in particular

- the chemical composition of the free stream,
- translational, rotational, vibrational, and electronic temperatures, and
- flow velocity

are essential for numerical rebuilding of the test configurations. The more measured data can be provided, the better the thermochemical properties at the inflow boundary of a numerical simulation can be matched to the actual experiment.

In many cases the measurement techniques applied for free stream characterization can be applied as well to measure the properties inside the shock layer. These measurements provide information in the middle of the considered flow field. Therefore the corresponding data offer capabilities for the validation of thermochemical models and numerical simulations which are not affected by surface effects as the measured heat flux data are.

7.1 Measurements at plasmatron facility U-13 (TsniiMash)

At the U-13 plasmatron facility of TsNIImash three different slug calorimeters will be used for heat flux evaluation at different catalycities. The heat receiving surfaces will be made of

- silver,
- copper, and
- quartz.

The silver calorimeter will be used for the evaluation of fully catalytic heat fluxes, while non-catalytic heat flux will be deduced from the quartz calorimeter.

For free stream characterization the following techniques will be applied in U-13:

- Pitot pressure measurements will provide the stagnation pressure.
- Emission spectroscopy will provide qualitative information on chemical species in the free stream.
- Microwave interferometry will be used for measuring electron density.

7.2 Measurements at plasmatron facility IPG-4 (IPM)

At the IPG-4 plasmatron facility of IPM heat fluxes will be evaluated for four different surface materials, i.e.

- silver,
- copper,
- stainless steel, and
- quartz.

Characterization measurements of the subsonic plasma flow will include the following measurements:

- Pressure measurements will include Pitot pressure and dynamic pressure.
- Emission spectroscopy will provide qualitative information on chemical species in the free stream.

7.3 Measurements at L2K (DLR)

Different techniques will be applied for heat flux evaluation at L2K. For the smaller model diameter of 50 mm, the water-cooled calorimeter shown in Fig. 12 will be applied to measure the heat flux to a copper surface. Additionally, a newly designed slug calorimeter (see Fig. 13) will be applied. Various plugs with different surface materials, i.e.

- silver,
- copper,
- stainless steel, and
- quartz.

will be used. The external shape body of the plug calorimeter is exchangeable. So, the plugs can also be used for heat flux measurements on the 100 mm cylinder model.

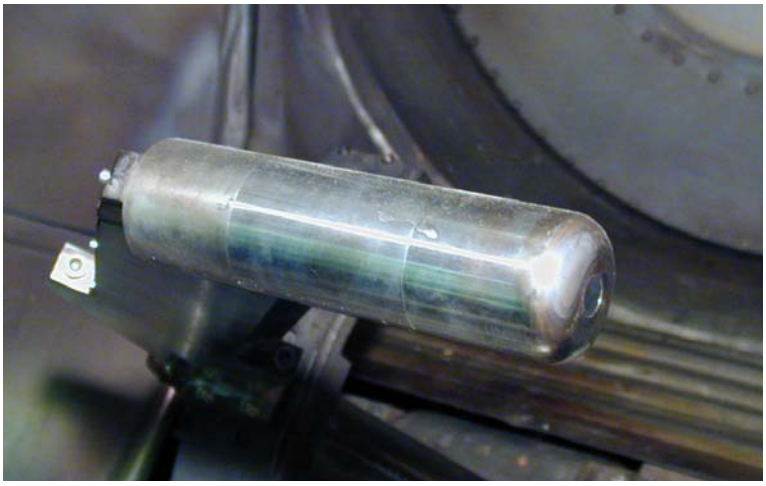


Fig. 12: DLR's water-cooled calorimeter.

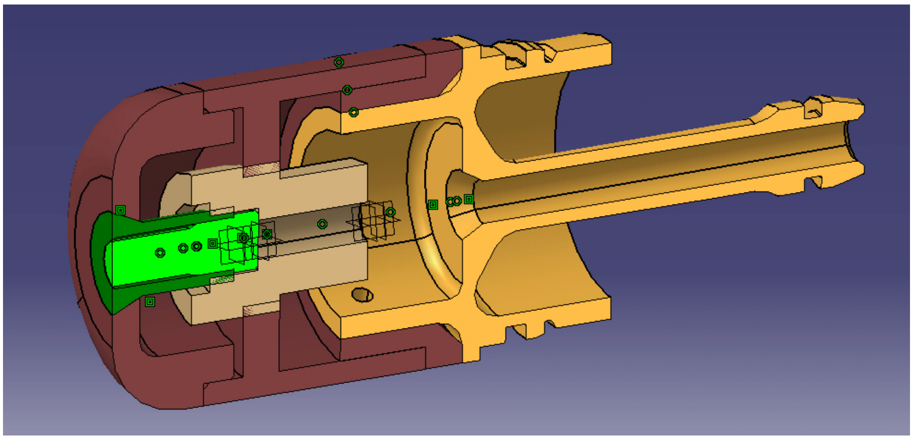


Fig. 13: DLR's slug calorimeter.

For comparison, a commercial heat flux microsensor (HFM) will also be applied in L2K. Due to its small dimensions (see Fig. 14) HFM can be used for local measurement of the stagnation point heat flux.

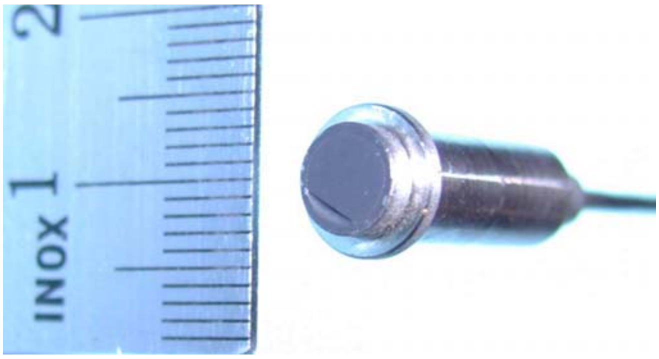


Fig. 14: HFM sensor.

The following auxiliary measurements will be performed to characterize the properties of the free stream and the shock layer:

- Lateral Pitot pressure profiles demonstrate the compliance to the test conditions.
- Diode laser absorption spectroscopy (DLAS) applied on CO molecules is used to measure the free stream velocity and the translational temperature in the free stream.
- Laser induced fluorescence (LIF) will be applied on NO and CO molecules to obtain spatially resolved profiles of vibrational and rotational temperatures in free stream and shock layer.
- Microwave interferometry will be used to measure electron density and velocity in the free stream.

7.4 Measurements at HEG (DLR)

The main focus of the tests in HEG is related to measurements on an instrumented model. In particular,

- pressure and
- heat flux rates

will be measured at various locations on the model surface at the specified test conditions. In addition to the sensor-based measurements the flow around the model will be visualized by Schlieren pictures.

During each run in HEG a permanent probe is installed in the test section. The probe is located off the nozzle's centre line at a radius of 200 mm. It is equipped with a Pitot probe. Additionally, a sphere with a radius of 10 mm is installed on this probe which records the stagnation point heat flux during each run. The readings of Pitot pressure and heat flux are used as reference values for other measurements.

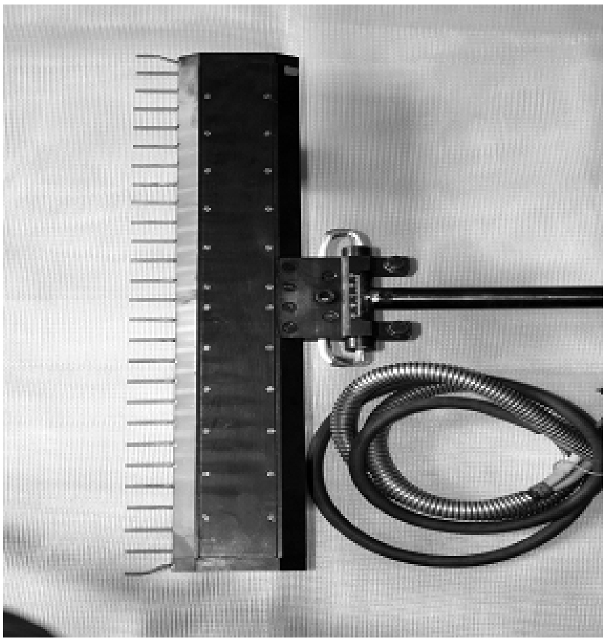
7.5 Measurements at IT-2 (TsAGI)

Corresponding to the test matrix (see Table 4) tests in TsAGI's facility IT-2 will be performed at test conditions FC-3 and FC-4. For this subtask a preliminary test sequence has been worked out which is listed in Table 5. Here, p_{ini} denotes the initial chamber pressure and p_t, T_t, h_t the expected values of total pressure, temperature, and enthalpy, resp. All the test runs will be performed at zero angle of attack. Multiple tests will help to reduce random errors. The tests will be performed at model position x = 200 mm, where the cylinder's front surface will be located in the middle of the optical window and flow visualization techniques can be applied.

Tests 1-10 will be performed at the standard conditions (p_t=350 bar, T_t=1730 K) of the facility which corresponds to test condition FC-4 defined in section 5 (see also Table 4). Tests 11-20 are required in order to identify appropriate operating conditions for test condition FC-3 at higher enthalpy. To increase the total enthalpy of the working gas, the initial filling of the chamber and by that the initial density of the working gas will be lowered. This sequence of tests will identify the maximal enthalpy $(h_t)_{max}$ the facility can be operated with. The corresponding operating conditions will be used for tests 21-32. Firstly, measurements on the model will be performed in tests 21-24. Afterwards flow characterization will be done at maximal enthalpy condition FC-3 by pressure and heat flux measurements using the rakes shown in Fig. 15. Measurements will be taken in both, vertical plane (φ = 0°) and horizontal plane (φ = 90°). For the standard conditions (p_t = 350 bar, T_t = 1730 K) the corresponding measurements were performed in previous test campaigns (see Fig. 7 and Fig. 8).

Table 5: Preliminary sequence of tests in the IT-2 facility

Test	p_{ini} [bar]	p_t [bar]	T_t [K]	h_t [kJ/kg]	Regime	Test object
1-5	40	350	1730	1930	standard	model, $\varphi = 0°$
6-10	40	350	1730	1930	standard	model, $\varphi = 90^0$
11,12	35	~300	~1910	~2180	higher enthalpy	model, $\varphi = 0°$
13,14	30	~285	~2170	~2530	higher enthalpy	model, $\varphi = 0°$
15,16	25	~250	~2525	~3020	higher enthalpy	model, $\varphi = 0°$
17,18	20	~230	~3040	~3740	higher enthalpy	model, $\varphi = 0°$
19,20	15	~200	~3870	~4940	higher enthalpy	model, $\varphi = 0°$
21,22	<40	<350	>1730	>1930	tbd	model, $\varphi = 0°$
23,24	<40	<350	>1730	>1930	tbd	model, $\varphi = 90^0$
25,26	<40	<350	>1730	>1930	tbd	pressure rake, $\varphi = 0°$
27,28	<40	<350	>1730	>1930	tbd	pressure rake, $\varphi = 90^0$
29,30	<40	<350	>1730	>1930	tbd	heat flux rake, $\varphi = 0°$
31,32	<40	<350	>1730	>1930	tbd	heat flux rake, $\varphi = 90^0$



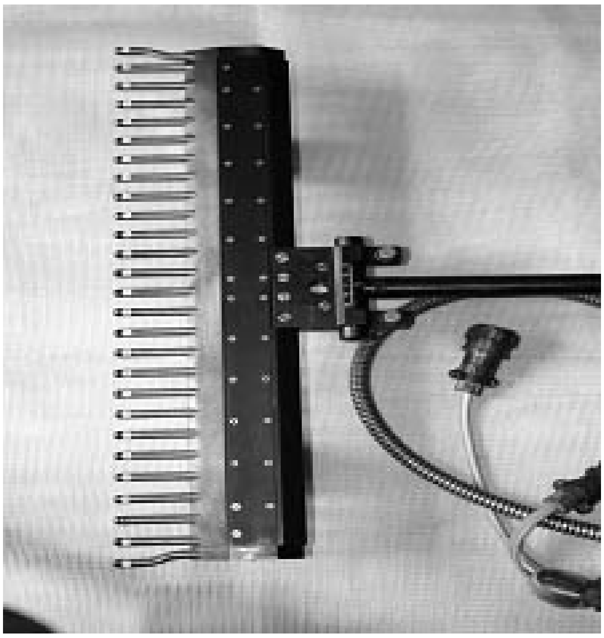


Fig. 15: Rakes with Pitot probes (left) and heat flux probes (right)

8 Summary and Conclusions

As a basis for the experimental activities in the frame of the SACOMAR study all participating high enthalpy ground test facilities were described with particular focus on the individual experiences and testing capabilities in Martian atmosphere. The characteristic properties of the participating facilities allow to cover all three important thermochemical regimes, i.e. equilibrium, non-equilibrium and frozen chemistry:

- In the plasmatron facilities U-13 and IPG-4 the flow is very close to thermochemical equilibrium, but subsonic.
- The flow in the two short duration facilities HEG and IT-2 is hypersonic and in thermochemical non-equilibrium.
- The arc heated facility L2K provides a hypersonic thermochemically frozen flow.

Based on the general requirements which were evaluated in WP 4 four test conditions could be identified which refer to the EXOMARS trajectory and enable direct facility-to-facility comparison

- at identical total enthalpy conditions in the reservoir, and
- at comparable free stream enthalpies in different thermochemical regimes.

As model geometry a flat-faced cylinder geometry with rounded edges was chosen, since it

- is a good representation of the windward surface of a capsule,
- provides largest possible shock stand-off distance in hypersonic flow maximizing the experimental possibilities of probing gas properties in the shock layer, and
- does not introduce additional complexity to numerical simulation.

Due to individual constraints, which either arise from facility size or from measurement techniques, a fully identical test geometry cannot be used in all facilities. For the plasmatron facilities the cylinder's diameter will be D = 50 mm and the edge radius r_e = 11.5 mm, for the short duration facilities the diameter will be D = 100 mm with the same edge radius. In the arc heated facility L2K both diameters will be tested.

Finally, a test matrix was defined specifying test conditions in terms of total enthalpy and Pitot pressure for each test facility. Based on the experiences and capabilities of the facilities, measurement techniques were specified to be applied for

- heat flux measurements and
- characterization of the free stream.

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