# 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**

| | |
|---|---|
| **Grant Agreement number:** | **263210-SACOMAR** |
| **Deliverable Reference Number:** | **D 1.2** |
| **Deliverable Title:** | **Final Report** |
| **Covered Period:** | **1.1.2011 – 30.6.2012** |

Due date of deliverable: 30th June 2011

Actual submission date: 12th November 2012

Start date of project: 20th January 2011

Duration: 18 months

Organisation name of lead contractor for this deliverable: DLR

Revision #: 1

| **Project co-funded by the European Commission within the 7th Framework Programme** | | |
|---|---|---|
| **Dissemination Level** | | |
| **PU** | Public | X |
| **PP** | Restricted to other programme participants (including the Commission Services) | |
| **RE** | Restricted to a group specified by the consortium (including the Commission Services) | |
| **CO** | Confidential, only for members of the consortium (including the Commission Services) | |

## Approval

| Title | issue | revision |
|---|---|---|
| *Final Report* | 1 | 1 |

| Author(s) | date |
|---|---|
| A. Gülhan | *12.11.12* |

| Approved by | date |
|---|---|
| G. Soos | |

## Table of Contents

## Nomenclature

| | |
|---|---|
| AD-PM | DLR Administration Department |
| AS-RF | Spacecraft Department of the DLR Institute for Aerodynamics and Flow Technology |
| AS-WK | Windtunnel Department of the DLR Institute for Aerodynamics and Flow Technology |
| ATD | Aerothermodynamics |
| CFD | Computational Fluid Dynamics |
| DLAS | Diode Laser Absorption Spectroscopy |
| DNS | Direct Numerical Simulation |
| DSMC | Direct Simulation Monte Carlo Method |
| HEG | DLR Shock Tunnel in Göttingen |
| IR | Infrared Thermography |
| IT-2 | Hot Shot Wind Tunnel of TsAGI |
| ITAM | Institute of Theoretical and Applied Mechanics |
| L2K | 1.4 MW Arc Heated Facility of DLR in Cologne |
| LIF | Laser Induced Fluorescence |
| MW | Micro wave |
| RANS | Reynolds-Averaged Navier-Stokes Equations |
| REA | Research Executive Agency |
| RTD | Research, Technology & Development |
| SICA | Specific International Cooperation Actions |
| TN | Technical Note |
| WP | Workpackage |

**Subscripts**

| | |
|---|---|
| 0 | Stagnation condition |
| $\infty$ | Free stream |

**Acronyms**

| | |
|---|---|
| CIRA | Centro Italiano Ricerche Aerospaziali |
| DLR | German Aerospace Centre |
| IPM | Institute for Problems in Mechanics |
| TsAGI | Central Aerohydrodynamic Institute |
| TsNIImash | Central Research Institute of Machine Building |

# 1 Declaration of the scientific representative of the project coordinator DLR

I, as scientific representative of the coordinator of this project and in line with the obligations as stated in Article II.2.3 of the Grant Agreement declare that:

- The attached periodic report represents an accurate description of the work carried out in this project for this reporting period;
- The project (tick as appropriate) [1]:

  ■ has fully achieved its objectives and technical goals for the period,

  ☐ has achieved most of its objectives and technical goals for the period with relatively minor deviations;

  ☐ has failed to achieve critical objectives and/or is not at all on schedule.

- The public website, if applicable

  ■ is up to date

  ☐ is not up to date
- To my best knowledge, the financial statements which are being submitted as part of this report are in line with the actual work carried out and are consistent with the report on the resources used for the project (section 3.4) and if applicable with the certificate on financial statement.
- All beneficiaries, in particular non-profit public bodies, secondary and higher education establishments, research organisations and SMEs, have declared to have verified their legal status. Any changes have been reported under section 3.2.3 (Project Management) in accordance with Article II.3.f of the Grant Agreement.

Name of scientific representative of the Coordinator: Dr.-Ing. Ali Gülhan..........................

Date: 12/ 11/ 2012

For most of the projects, the signature of this declaration could be done directly via the IT reporting tool through an adapted IT mechanism.

[1] If either of these boxes below is ticked, the report should reflect these and any remedial actions taken.

# 2 Publishable Summary

When entering a planetary atmosphere the high speed deceleration of blunt bodies leads to a strong bow shock formation in front of a capsule and heating of the gas and subsequent heating of the vehicle. The internal structure of the vehicle is thermally protected using a Thermal Protection System (TPS). Most of the capsules use a TPS based on ablation materials. The modelling of complex chemical processes in the boundary layer flow around the ablation and inside the ablation materials is very challenging and needs reliable experimental data gained by means of sophisticated measurement techniques. In order to extract the influence of different parameters on the aerothermal heating during Martian entry a study on selected and well defined materials is an important step. **Figure 1** shows a typical test configuration on the sample in Martian atmosphere.

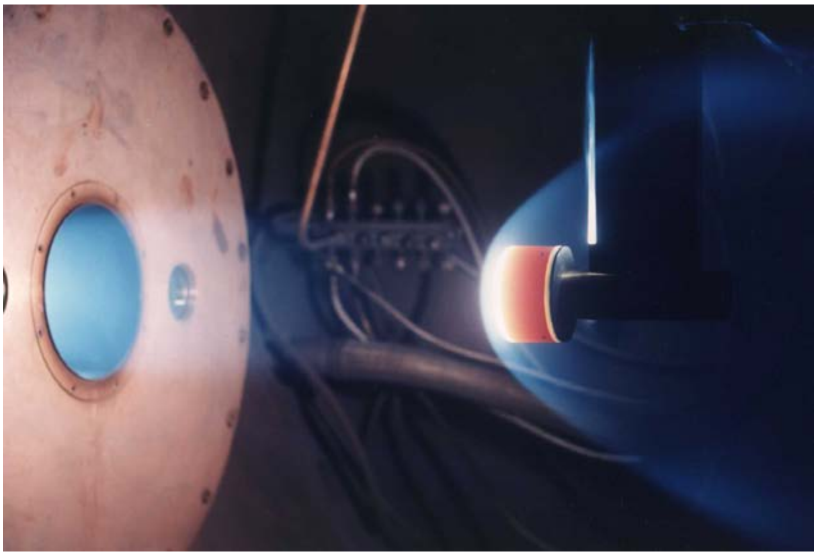


**Figure 1: High temperature non-equilibrium flow phenomena around a capsule**

## 2.1 Objectives

The main objective of SACOMAR is the experimental and numerical study of gas-surface interaction phenomena in the high enthalpy flow field behind the bow shock in front of a model at Martian entry flow conditions. The improvement of physical modelling using experimental data and its implementation into numerical simulation codes is essential to understand and interpret the physical processes. At the end the project will allow to estimate the aerothermal loads on the vehicle more accurately. Main activities of the project are:

- Definition of requirements on experiments, modelling and CFD codes using realistic Mars mission profiles
- Experiments on the measurement of flow parameters in the free stream and behind the shock and stagnation point heat flux rate
- Improvement of existing physical models with respect to non-equilibrium effects, transport properties and gas-surface interaction chemistry
- Implementation of improved physical models into the CFD codes and simulation of experiments
- Synthesis of the data and reporting

## 2.2 Achievements

In the reporting period following goals were achieved:

- A project ftp server and project portal on web-site base have been established,
- A reliable data base resulting from experimental and numerical studies for the design of future Mars missions has been created,
- The knowledge on Martian entry has been extended and can be transferred for future interplanetary missions.
- The co-operation between EC and Russia worked very well and will help to intensity the collaboration in future space programmes.
- SACOMAR activities have been presented in several international conferences and published in journals.

# 3 Core of the report for the period: Project objectives, work progress and achievements, project management

## 3.1 Project objectives for the reporting period

The main objective of SACOMAR is the experimental and numerical study of gas-surface interaction phenomena in the high enthalpy flow field behind the bow shock in front of a model at Martian entry flow conditions. The improvement of physical modelling using experimental data and its implementation into numerical simulation codes is essential to understand and interpret the physical processes. At the end the project will allow to estimate the aerothermal loads on the vehicle more accurately. The main objectives of the reporting period of the project were:

- A reliable data base resulting from experimental and numerical studies for the design of future Mars missions,
- New knowledge will be transferred for future interplanetary missions. A new generation of researchers will take advantage of working on long term activities that can meet the future needs of aerospace industry.
- Intensified co-operation between EC and Russia in space programmes
- A selected, well structured and efficient EC-Russian team with reasonable resources to develop the experimental and numerical aerothermodynamic tools for future missions,
- Dissemination activities beyond the consortium, of the numerical tools and technology produced, including publications, conferences and exploitation of the results produced by the team.

## 3.2 Work progress and achievements for the reporting period

### 3.2.1 WP1

**WP title: Project Management**

**Responsible partner: DLR**

**Workplan according to DoW**

- Effective management and coordination of the project to ensure high technical and economical efficiency
- The overall legal, financial and administrative management
- Control of financial and budgetary means of the project and supply of all necessary deliverables
- Decision on the evolution of the project as it progresses with respect to its milestone achievements

**Achievements**

All milestones of the project in this reporting period have been achieved.

### 3.2.2 WP2

**WP title: Technical Coordination**

**Responsible partner: DLR**

**Workplan according to DoW**

Each work package will provide bi-monthly a short status report on the work progress obtained, inform about possible delays and indicate any problems. Critical points will be reported in particular those which endanger the objectives of the project or delay the input towards other work packages.

Depending on the progress made, dedicated teleconferences will be organized by the coordinator with the work package leaders, to discuss the possible problems, propose solutions for the sake of the project.

**Achievements**

The good technical coordination of SACOMAR allowed having strong interaction between experimental, modelling and numerical activities. This allowed achieving partially unique results concerning the aerthermodynamic issues of Martian entry.

### 3.2.3 WP3

**WP title: Dissemination**

**Responsible partner: DLR**

**Workplan according to DoW**

Project information and objectives for the outside world will be made available by a dedicated portal on the web-site of the coordinator. The coordinator will also represent the project at symposia, conferences, etc. to disseminate and present as widely as possible general or detailed technical information about the project and technical achievements.

**Achievements**

For the presentation of the project and information exchange with the project partner and European scientific community, a ftp server (sacomar@ftp.dlr.de) and a project portal on the web-site (www.dlr.de/as/sacomar) have been established. The SACOMAR project has been presented with following paper and book contributions:

1. Gülhan, A.; Improvement of Experimental and Numerical Tools for Safe and Controlled Martian Entry, 9th International Planetory Probe Workshop, Toulouse / France, 2012.

2. Kovalev, R. V., Gorschkov, A. B., Rudin, N. F., Vlasov, V. I., Zalogin, G. N.; Experimental and Numerical Simulation of Martian Entry Conditions, 9th International Planetory Probe Workshop, Toulouse / France, 2012

3. A. Koleshnikov, A. Gordeev, S. Vasilevski; Simulation of heat transfer and surface catalysis for Exomars entry conditions, 9th International Planetory Probe Workshop, Toulouse / France, 2012.

4. Egorov, I.; Results of Experimental Study in TsAGI IT-2 Hot Shot Wind Tunnel, 9th International Planetory Probe Workshop, Toulouse / France, 2012.

5. Mario De Stefano Fumo, Pietro Catalano, Burkard Esser, Ali Gülhan; Numerical Modelling of the $CO_2$-$N_2$ Hypersonic Flow, 63rd International Astronautical Congress, Naples, Italy IAC-12, A3,3A,19.p1, 2012.

6. A. Gülhan; SACOMAR (Technologies for Safe and Controlled Martian entry), The Parlament Magazine, p. 95, 26.03.2012.

7. A. Gülhan; Technologies for Safe and Controlled Martian Entry, Contribution to the EU Book ‘Let’s Embrace Space’, to published in 2012.

### 3.2.4 WP4

**WP title: Requirements and Synthesis**

## Task 4.1: Requirements

### Responsible partner: TAS-I

### Workplan according to DoW

This task has the following main objective:

- Definition of the requirements for the modelling, simulation and testing activities to be conducted in the framework of the SACOMAR project.

### Achievements

According to the workplan, the following main activities have been performed by TAS-I:

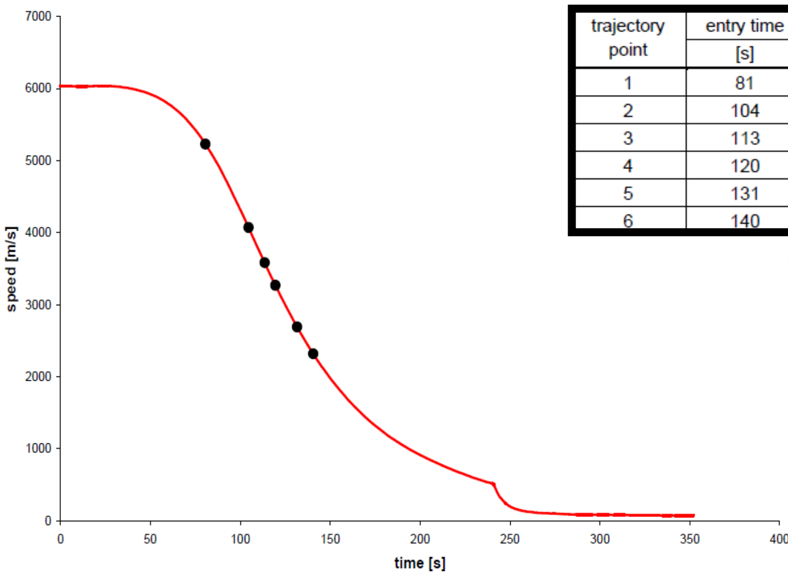
- Overview on the current physico-chemical modelling techniques for CO2 high enthalpy flows, including transport properties, gas phase kinetics and surface chemistry, their status and chances for improvement.

- Identification of type of CFD simulations needed to gather information about the implementation of the developed models, and of a standard method for data exchange,

- Definition of the requirements on the experimental activity to be performed to exploit the Martian atmosphere's relevant properties in a typical entry trajectory,

- Definition of criteria for the validation of numerical simulations results over experimental data, and of their use for the extrapolation to flight task.

As shown in Fig. 2 the most critical trajectory points with respect to aerothermal loads are defined for the simulation. Complete details are provided in the SACOMAR deliverable D4.1 (Requirements on Modelling and Simulation).




| trajectory point | entry time [s] | velocity [m/s] | enthalpy [MJ/kg] | Pitot pressure [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 |

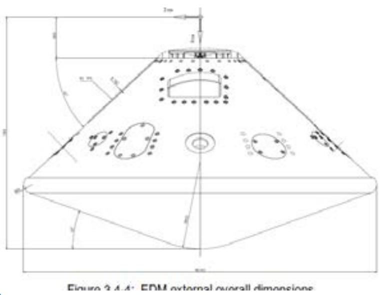


**Fig. 2: Selected SACOMAR trajectory points [2].**

## Task 4.2: Synthesis

**Responsible partner: TAS-I**

**Workplan according to DoW**

This task has the following main objective:

- Synthesis of achieved results with respect to their application for future missions.

### Achievements

The synthesis of the experimental and numerical work has been carried out. Critical assessment of the code-to-code validation and experiment-numeric comparison identified main outcome of the study with respect to the transport properties, thermal non-equilibrium and surface catalysis at Martian entry conditions.

TAS-I synthesis made clear that the shock stand-off distance, which is strongly linked to the thermo-chemical behavior of the gas in the shock layer, shows partially remarkable differences in the data of different codes. It was also the case for the temperature along the stagnation line from free stream to the model surface (**Fig. 3**) [3]. The strong deviation of the ITAM data is mainly related to the use of an DSMC code for rarefied gases in comparison to the Navier-Stokes (NS) computations for continuum flow. The difference is more significant for the TP2, which is definitely in the continuum flow regime and therefore not suitable for DSMC computation. Another remarkable difference compared to the majority of the results is the data of the TAS-I NS-code. This study led to an improvement in the TAS-I code with respect to the transport properties and the treatment of thermal non-equilibrium effects. Such improvements in an industrial code, which is used for the design of spacecrafts, can be considered as an important achievement of SACOMAR.

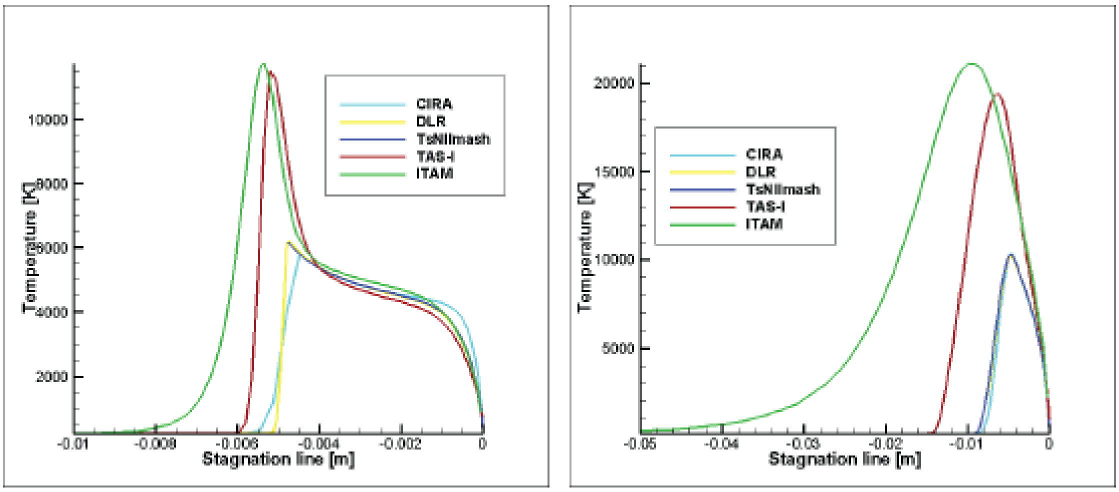



**Fig. 3: Computed stagnation line temperature for TP1 (left) and TP2 (right) [3].**

While the DLR code TAU uses on temperature model, The codes of CIRA and TsNIImash use a two temperature model. The DSMC code of ITAM considers three translational, rotational and vibrational temperatures. The code of TAS-I uses besides the translational temperature, which is equal to the rotational temperature, 5 vibrational temperatures for all major molecules in the flow.

**Table 1: Temperature model of different codes [3]**

| code | Temperature set |
|---|---|
| CIRA | T, $T_v$ |
| DLR | T |
| TsNIImash | T, $T_v$ |
| ITAM | $T_{trasl}$, $T_{rot}$, $T_v$ |
| TAS-I | T, $T_v(CO_2)$, $T_v(N_2)$, $T_v(O_2)$, $T_v(NO)$, $T_v(CO)$ |

The main outcome of SACOMAR was the improvements in the thermochemical model and transport proporties of the TAS-I code, which is the design tool of the industry. Finally the comparison of computed heat fluxes is listed in **Table 2**. As it can be seen the agreement between computed heat fluxes is reasonable. A bit more significant deviation between the NS solvers and the DSMC solver of ITAM is also acceptable, since the code was used at almost the edge of its application area.

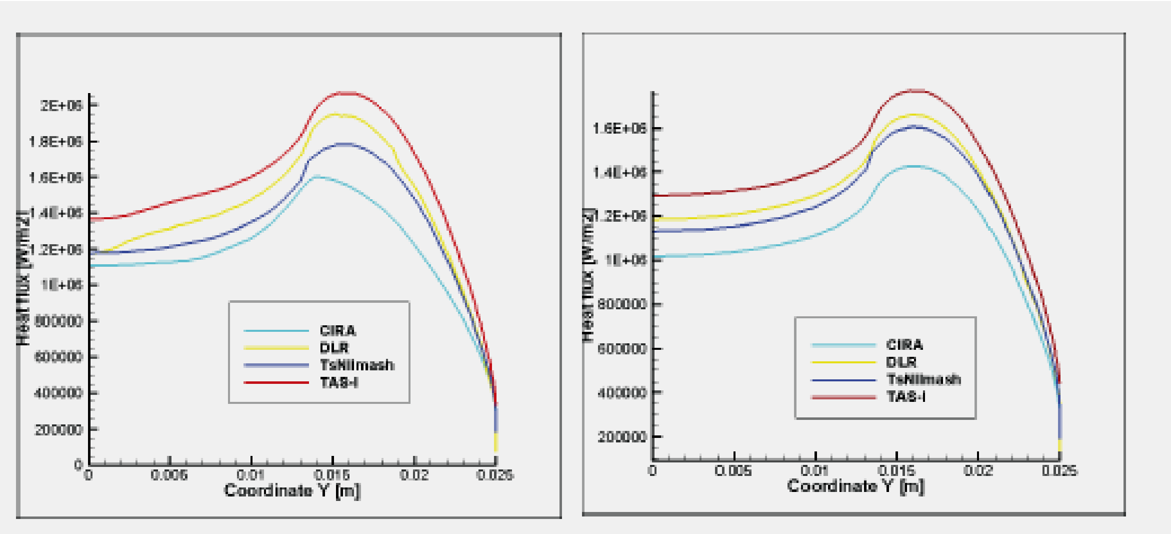



**Fig. 4: Heat flux rates to the same model computed with different codes for TP 1 (left) and TP 2 (right) [3].**

**Table 2: Computed heat fluxes with different codes [3]**

| Case | CIRA (Fluent) | DLR (TAU) | TsNIImash | ITAM (SMILE) | TAS-I |
|---|---|---|---|---|---|
| std_tp1_fc | 1100 | 1175 | 974 | | 1096 |
| std_tp2_fc | 980 | 1185 | 924 | | 1039 |
| std_tp1_nc | 700 | 688 | 515 | 802 | 709 |
| std_tp2_nc | 610 | 723 | 508 | 1101 | 710 |
| lrg_tp1_fc | 650 | 651 | 677 | | 709 |
| lrg_tp2_fc | 590 | 715 | 614 | | 602 |
| lrg_tp1_nc | 350 | 415 | 332 | | 349 |
| lrg_tp2_nc | 260 | 307 | 262 | 482 | 275 |

The results of the study have been reported in the deliverable 4.2 (Synthesis of main results of the modelling and simulation) [3].

### 3.2.5 WP5

**WP title: Aerothermal tests**

**<u>Task 5.1: Test plan</u>**

**Responsible partner: DLR**

**Workplan according to DoW**

This task has the following main objectives:

- Review of experience and facility capabilities of DLR, TsNIImash, TsaGI and IPM with respect to $CO_2$+ $N_2$ high enthalpy flows
- Definition of test conditions in terms of total enthalpy and Pitot pressure

**Achievements**

After a detailed analysis of the performance of testing facilities and their comparison with the important trajectory data points of the Exomars entry phase, a test plan has been defined. With reference to the EXOMARS trajectory four test conditions were identified which enable direct facility-to-facility comparison.

Finally, a test matrix was defined specifying test conditions in terms of total enthalpy and Pitot pressure for each test facility (Table 3). Based on experiences and capabilities of the facilities, measurement techniques were specified to be applied for heat flux measurements and flow characterization. The test matrix and test models including the instrumentation have been described in the SACOMAR deliverable D5.1 (Test plan for Experiments) [4].

**Table 3: EXOMARS test matrix [4]**

| 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 |

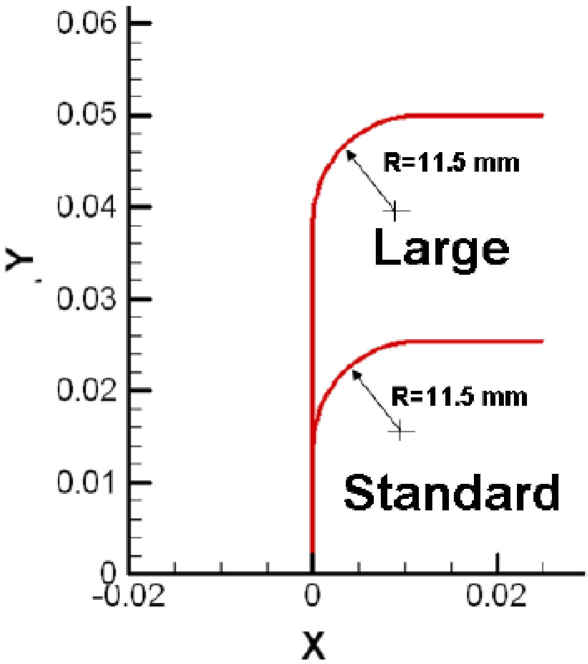



**Fig. 5: Test model geometries [24]**

<u>**Task 5.2: Tests in HEG shock tunnel**</u>

**Responsible partner: DLR**

**Workplan according to DoW**

According to the description in the DoW, the test model has to be manufactured, instrumented and installed in the test section of the shock tunnel HEG. Tests have to be carried out at two test conditions as defined in the DoW. The free stream has to be calibrated experimentally before the tests. The main measured parameters are the shock stand-off distance using the Schlieren technique, pressure distribution and heat flux distribution in the free stream and on the model surface.

**Achievements**

The instrumented test model was manufactured and installed into the HEG test section. All calibration and main tests with CO2 flow have been performed successfully. The comparison between computed and measured shock stand-off distance is quite good (Fig. 6:).

The results of this work have been described in the SACOMAR deliverable D5.2 (Results of Experimental Study in the High Enthalpy Shock Tunnel Göttingen (HEG))[8].

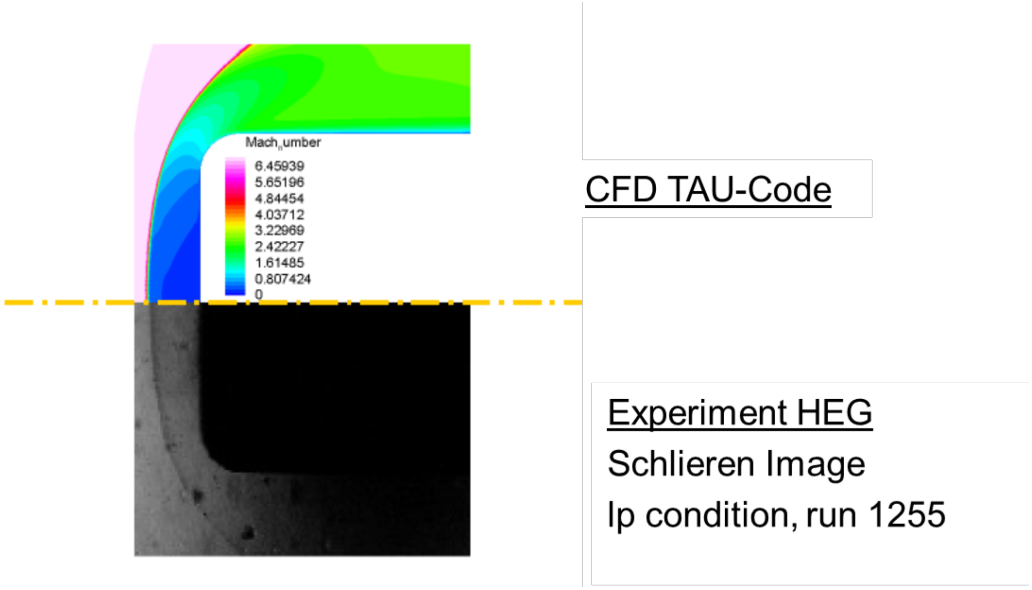



**Fig. 6: Hybrid CFD Mesh around SACOMAR wind tunnel test probe (and MatchingTAU-Code Result Compared to Experimental Schlieren Image, Solution for HEG Test Condition Mach 6.86, after One Adaptation Cycle) [21][8].**

**<u>Task 5.3: Tests in IT-2 facility</u>**

**Responsible partner: TsAGI**

**Workplan according to DoW**

This task has the following main objectives:

- Model designing, manufacturing and equipping with heat flux and pressure gages
- Measurement of stagnation pressure and heat flux distributions in the test section
- Model tests in IT-2 wind tunnel in $CO_2$ flow at $M_\infty$=12 using Schlieren visualization according test plan

**Achievements**

As mentioned before numerical rebuilding have been carried out for all experiments. This step should show the ability and shortcomings of these codes. We start with the relatively low enthalpy experiments in the IT-2 facility of TsAGI. The main outcome of this activity was the demonstration of the effect of the $CO_2$ dissociation on the specific heat ratio, which leads to change in the shock stand-off distance. Such results are very rare in the literature.

Effective values of specific heat ratio γ of $CO_2$ have been obtained by TsAGI for all test three flow test regimes based on the values of the bow shock stand-off distance. These bow shock stand-off distances were experimentally determined by evaluation of the shadowgraphs taken in IT-2 (averaging the distances over several test runs for each flow regime) and allow for a comparison to the shock stand-off distances determined by CFD for Regime 1 to 3. Fig. 7 shows measured shock stand-off distances resulting from evaluation of the IT-2 test data in comparison with the CFD data generated by TAU simulations.

The results of this work have been described in the SACOMAR deliverable D5.3 (Results of experimental study in TsAGI IT-2 Hot Shot wind tunnel) [9].

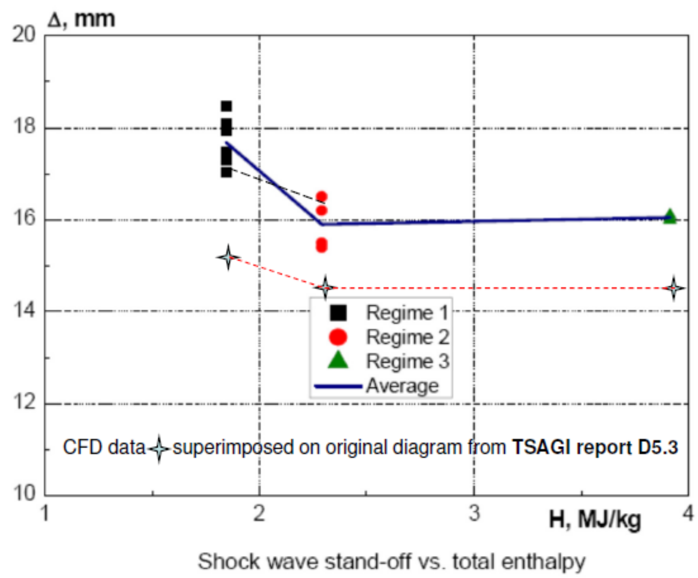



**Fig. 7: Shock stand-off distances for the IT-2 regimes 1,2 and 3 [9][21].**

## Task 5.4: Tests in Plasmatron facility IPG-4

**Responsible partner: IPM**

### Workplan according to DoW

This task has the following main objectives:

- Manufacturing of the test models for experiments in IPG-4
- Measurement of the free stream and boundary layer spectra with emission spectroscopy
- Measurement of enthalpy in plasma free stream
- Measurement of the heat flux rate to the model and to reference probe with silver coating (fully catalytic) and quartz coating (non-catalytic surface)

**Achievements**

A 50-mm-diam water-cooled test model from copper and brass, and water-flow heat flux probe from stainless steel are manufactured in the Laboratory for Plasma/Surface Interaction. Subsonic heat transfer tests with pure CO2 plasma have been performed in the wide range of enthalpy (17.2 – 4.2 MJ/kg), stagnation pressure (80 and 40 hPa) and gas flow rate (1.5 – 2.5 g/s).

Measurements of the heat flux rates to the model with the reference probe with silver surface at selected generator power and stagnation pressures have been performed. Evidence of silver surface oxidation was observed. The time history of the stagnation point heat flux to the silver wall was registered. The saturation time for reaching maximum heat flux is found to be about 15 min.

Indirect numerical rebuilding by GAMMA CFD code of the flow enthalpy through calculated heat flux rates to cooled fully catalytic wall and comparison with the data of stagnation point heat fluxes to oxidized stable silver surface of the reference probe was carried out.

Fig. 8 shows a summary of measured and calculated catalytic behaviour of different materials. It is clearly noticeable that the order of surface catalysis starting from most catalytic one is silver, copper, silver and quartz. The dashed lines of theoretical results describe calculated heat flux using the standard model. Solid lines show computed heat fluxes using the novel model, which is validated with the data of the SACOMAR project. The improvement is remarkable.

The results of this work have been described in the SACOMAR deliverable D5.4 (Results of the experimental study in the IPG-4 facility) [10].

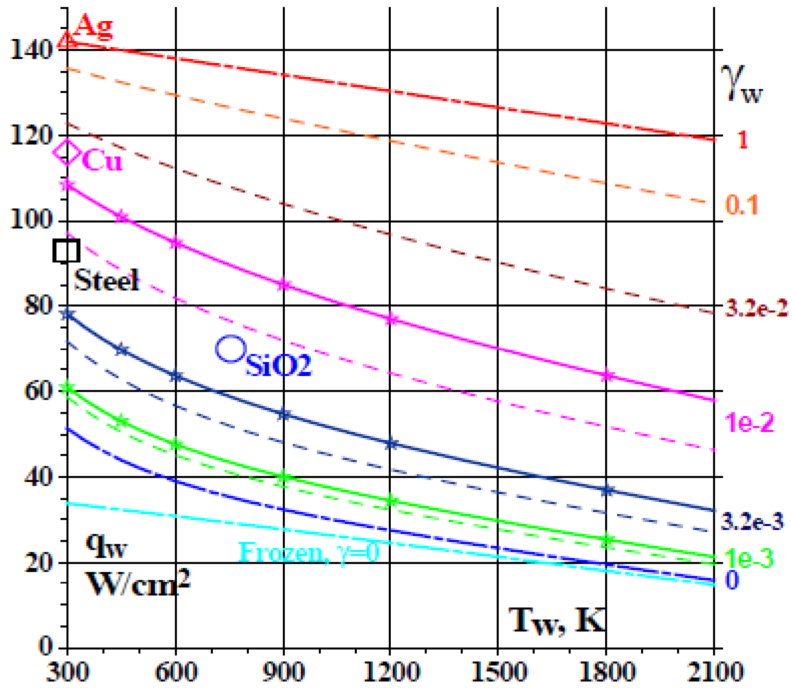



**Fig. 8: Measured and computed heat flux rates for different surfaces in the Martian high enthalpy flow of the IPG-4 facility [10][22].**

## Task 5.5: Tests in Plasmatron facility U-13

**Responsible partner: TsNIImash**

**Workplan according to DoW**

This task has the following main objectives:

- Design and manufacturing of a test model with instrumentation
- Characterization of the flow field using Emission Spectroscopy technique
- Tests performance in CO2 + N2 environment in the TsNIImash U13 Plasmatron facility

**Achievements**

Test model (water-cooled calorimeter shaped as ESA standard geometry of 50 mm in diameter) with three receiving elements (silver, copper and quartz) were designed and manufactured in accordance with the Test plan (SACOMAR deliverable D5.1). Emission spectra of CO2 + N2 flow were measured for all flow regimes of test matrix.

A dedicated study concerning the catalytic effects on the heat flux rate has been carried out by TsNIImash. TsNIImash performed tests on different catalytic surfaces, i.e. silver, copper and steel [11]. The rebuilding of this tests shows that the final finishing of the silver surface or oxidation process has an important effect on the surface catalysis [23]. Copper surface has a comparable catalycity like electrolyte silver used for the tests (see Fig. 9). The quartz surface seems to be low catalytic.

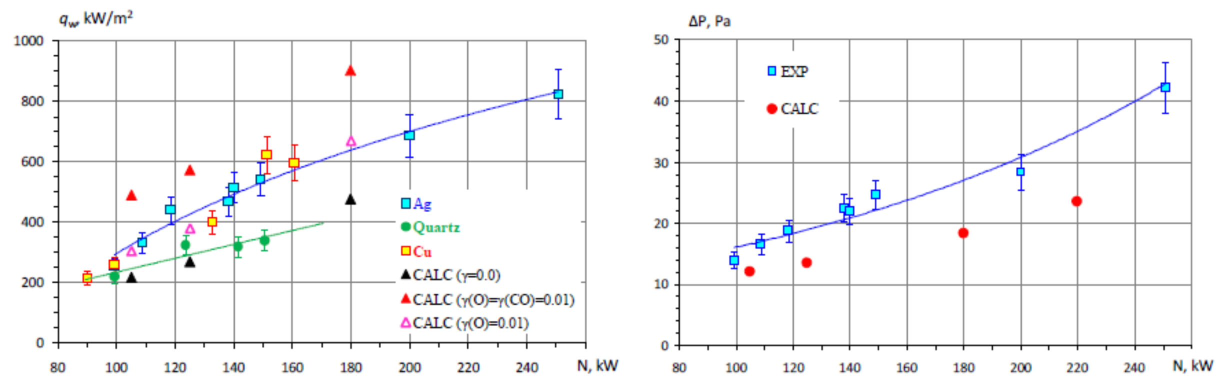



**Fig. 9: Experimental and numerical heat fluxes (left) and Pitot pressures (right) at 80 mbar condition in the U-13 facility of TsNIImash [11][23].**

Test results of this work have been described in the SACOMAR deliverable D5.5 (Results of experimental study in the TsNIImash Plasmatron facility U13) [11].

## Task 5.6: Tests in arc heated facilities

**Responsible partner: DLR**

**Workplan according to DoW**

- Design and manufacturing of a test model with instrumentation
- Characterization of the flow field using spectroscopic techniques like Emission Spectroscopy, LIF, DLAS and Micro-Wave Interferometry
- Measurement of the heat flux rate and pressure on the model surface at defined flow conditions in $CO_2$+ $N_2$ environment in the arc heated facility L2K

## Achievements

Two different test conditions had been defined in the SACOMAR test plan. The first test condition FC-1 is characterized by a high total enthalpy of 13.8 MJ/kg. The enthalpy level of the second test condition FC-2 is considerably lower at 9.0 MJ/kg. For these two conditions a large number of measurements was performed both, in the free stream and in the shock layer of two flat-faced cylinder models with diameters of 50 mm and 100 mm.

In the first subset of tests, the cold wall heat flux in the stagnation point of the models was measured with different techniques, i.e. a so-called heat flux microsensor (HFM) and a slug calorimeter made of stainless steel. The results obtained with these techniques are compared in Table 4. The listed values indicate that the slug calorimeter generally provides lower heat fluxes when compared to the HFM measurements. Taking HFM as reference the reduction is between 28% and 36%, i.e. nearly constant. Therefore, the differences might be regarded as systematic. A possible explanation could be the different surface catalycity. The surface of the HFM sensor is known to be almost fully catalytic, while stainless steel is only partly catalytic. The heat flux reduction of about 30% fully agrees to the measurements in the IPM plasmatron facility in the frame of SACOMAR task 5.4.

**Table 4: Comparison of heat flux measurements [12].**

| Test condition | Model diameter | Pitot pressure | Heat flux rate [kW/m$^2$] | | |
|---|---|---|---|---|---|
| | [mm] | [hPa] | HFM | Calorimeter | |
| | | | | Slug | Water-cooled |
| FC-1 | 100 | 20 | 891 | 640 | |
| | 50 | 20 | 1091 | 740 | 830 |
| | 50 | 80 | - | 1380 | 1680 |
| FC-2 | 100 | 20 | 518 | 355 | |
| | 50 | 20 | 694 | 440 | 570 |
| | 50 | 80 | - | 630 | 1000 |

In addition to the heat flux measurements several spectroscopic measurement techniques were applied for free stream characterisation. NO molecules were observed by laser induced fluorescence (LIF), while CO was probed by diode laser absorption spectroscopy (DLAS).

From NO-LIF measurements spatially resolved temperature profiles were obtained in the free stream and in front of the flat-faced cylinder models. The absolute temperature level in the free stream was found higher for the low enthalpy test condition FC-2 compared to high enthalpy condition FC-1. This result can only be explained by differences in the chemical gas composition inside the facility's reservoir which shows a higher fraction of $CO_2$ for FC-2. Since the reservoir condition can be determined from accurate measurements of gas mass flow rate and reservoir pressure, the L2K nozzle flow is an excellent test case for validation of thermochemical models of Martian atmosphere.

Measurements with NO-LIF in the shock layer at different distances to the model surface provided an almost constant temperature level along the stagnation point stream line until the edge of the boundary layer (Fig. 10). In addition, the good spatial resolution allowed to extract the position of the bow shock from the lateral profiles and to estimate the shock shape and the shock's stand-off distance. The stand-off distance was found to be 21 mm for the 100 mm model, while it was only about 11 mm for the 50 mm model.

Microwave interferometry and DLAS were mainly applied for velocity measurements. Velocities in the range of 2700 m/s and 3100 m/s were measured for test conditions FC-1 and FC-2, resp. In addition to microwave interferometry, which was only applied at a position 350 mm to the nozzle exit, DLAS measurements was also applied at a more upstream location (Fig. 11). As could be expected, only a minor influence was observed in the measured velocities. The measured temperatures, however, show a proper tendency, because significantly higher temperatures are measured at the upstream location. With respect to temperature measurements, it has, however, to be taken into account that DLAS is a line-of-sight method. This property can explain the difference to the measurements with NO-LIF which is a local measurement and provided slightly lower temperatures.

Test results of this work have been described in the SACOMAR deliverable D5.6 (Results of the experimental study in the L2K Facility)[12].

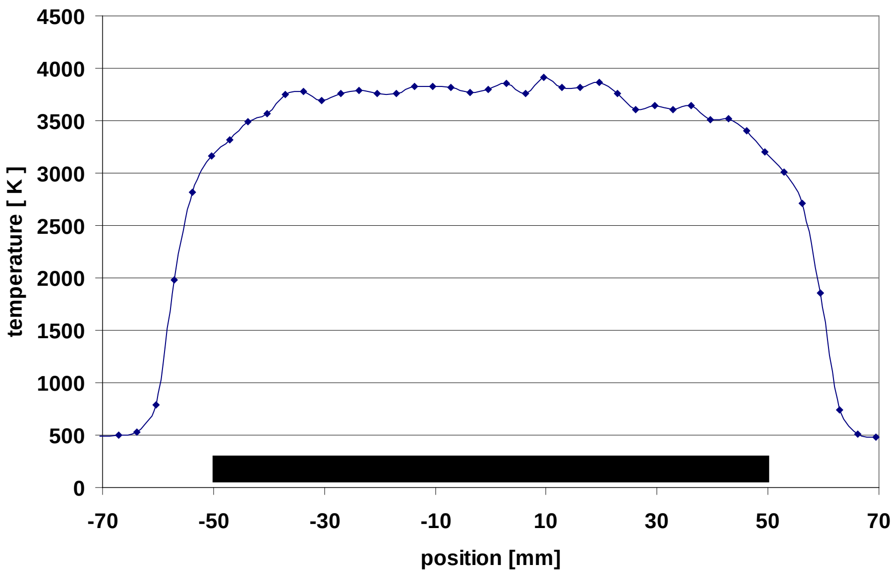



**Fig. 10: Temperature profile 3 mm in front of the 100 mm model at test condition FC-1 [12].**

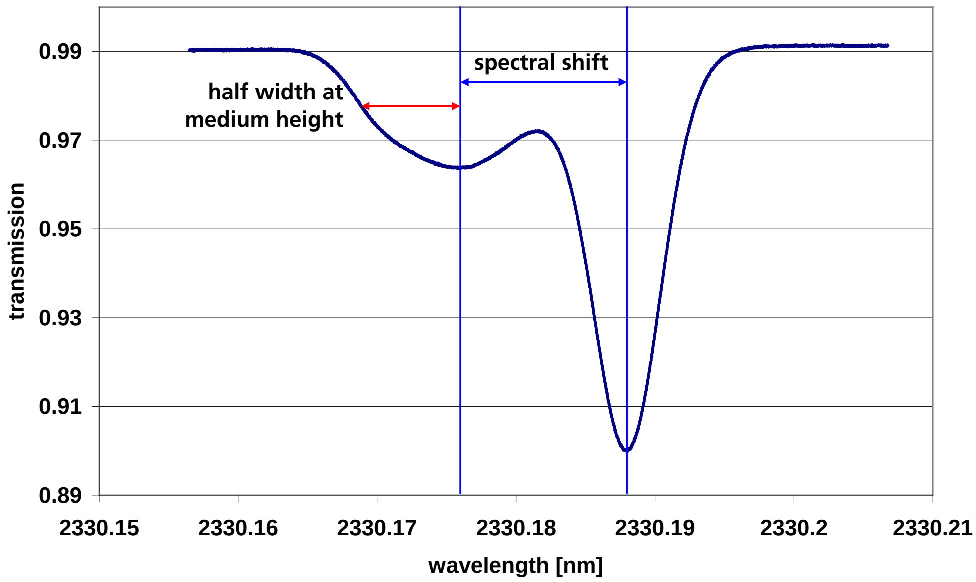



**Fig. 11: Results from DLAS measurement at flow condition FC-1 [12]..**

### 3.2.6 WP6

**WP title: Physical-Chemical Modelling**

**Task 6.1: Review of physical-chemical modelling**

**Responsible partner: ASTRIUM**

#### Workplan according to DoW

The objective of this task is a review of the existing thermochemical models for the Mars atmosphere's gas mixture including transport, dissociation, ionization and surface catalysis and the related validation status / associated uncertainties. Suggestions for further improvements of the modelling serve as basis for further careful discussion within WP1 and WP2, so as to refine the further course of action regarding implementation of the most promising model improvements and the related experimental conditions rebuilding.

#### Achievements

The current state of the art regarding physico-chemical modelling of the Mars atmospheric gas mixture has been reviewed with respect to:

- Modelling of Thermal State
- Chemical Kinetics
- Transport Properties
- Surface Catalysis

Uncertainties related to the current models as well as promising directions for possible improvement within the experimental and numerical rebuilding work foreseen in the SACOMAR study were identified for each of these areas.

The results of the work performed have been described in the SACOMAR deliverable D6.1 (Review of Physico-Chemical $CO_2$ Modelling and Recommendation for Improvement) [13].

### Task 6.2: Gas Transport Properties

**Responsible partner: TsNIImash**

**Workplan according to DoW**

This task has the following main objectives:

- Development of library of thermodynamic and transport properties for the Mars mixture
- Assist in development of interface for the CFD codes

**Achievements**

Appropriate thermodynamic information for constituent species has been gathered. Available interaction potentials have been gathered and collision integrals required for calculation of transport phenomena have been estimated.

The results of the work performed have been described in the SACOMAR deliverable D6.2 (Report on gas transport properties) [14].

### Task 6.3: Gas Phase Chemistry

**Responsible partner: DLR**

**Workplan according to DoW**

This task has the following main objectives:

- Selection of a non-equilibrium model for the gas compositions used in the experiments
- Implementation of the model in the CFD code

**Achievements**

After review of suitable $CO_2$ reaction models an appropriate reaction scheme containing 27 reactions for the species $CO_2$, CO, C, $O_2$, O and $C_2$ and 103 reactions for the species $CO_2$, NCO, CO, $N_2$, $O_2$, $C_2$, CO, NO, N, C and O has been implemented. Transport properties are modelled via Wilke's mixing rules which require single species viscosities as input. Diffusion is determined from mixture viscosity employing a user defined Schmidt number. For the simulation of $CO_2$ flows a Schmidt number of 0.7 is proposed.

The results of the work performed have been described in the SACOMAR deliverable D6.3 (Report and library on gas phase chemistry) [15].

**Task 6.4: Surface Chemistry**

**Responsible partner: IPM**

**Workplan according to DoW**

This task has the following main objectives:

- Gather appropriate information for surface catalycity
- Gather appropriate information for diffusion on the surface
- Comparative analysis all of the heat transfer data and determination catalycity of different surfaces (metals and quartz)

**Achievements**

The main references of literature related to O and CO catalytic recombination have been selected. The appropriate data of catalytic recombination coefficients of atomic oxygen on cold and hot surfaces of some metals and quartz were gathered. The structure of electronic library is chosen providing the data of effective recombination coefficients, actual recombination coefficients and energy accommodation coefficients for O atoms and CO molecules. Existing models of catalytic recombination of O atoms and CO molecules were considered, analyzed and one model is chosen for further modelling catalycity heating effect on metals and quartz. Through qualitative comparative analysis of measured stagnation point fluxes the catalytic scale is estimated as follows: Ag $>$ Mo $\cong$ Cu $>$ $SiO_2$.

The results of the work performed have been described in the SACOMAR deliverable D6.4 (Report and library on surface chemistry) [16].

### 3.2.7 WP7

**WP title: CFD simulation**

For the code to code validation the geometry of the models for ground testing was used to compute flow properties at two Exomars flight trajectory points. Fig. 5 shows selected geometries. The parameters of selected flight points are listed in Table 5.

**Table 5: Test matrix for code-to-code validation**

| Case | Model diameter [mm] | Mach | P∞ [Pa] | T∞ [K] | Wall |
|---|---|---|---|---|---|
| std_tp1_fc | 50 | 17.32 | 22.46 | 222.92 | fully catalytic |
| std_tp2_fc | | 30.17 | 0.95 | 155.20 | |
| std_tp1_nc | | 17.32 | 22.46 | 222.92 | non catalytic |
| std_tp2_nc | | 30.17 | 0.95 | 155.20 | |
| lrg_tp1_fc | 100 | 17.32 | 22.46 | 222.92 | fully catalytic |
| lrg_tp2_fc | | 30.17 | 0.95 | 155.20 | |
| lrg_tp1_nc | | 17.32 | 22.46 | 222.92 | non catalytic |
| lrg_tp2_nc | | 30.17 | 0.95 | 155.20 | |

Table 11 - test matrix for code to code validation

**Task 7.1: CIRA code modelling validation**

**Responsible partner: CIRA**

**Workplan according to DoW**

- Implementation of modelling and numerical improvements to the CIRA code.
- Validation of modelling and numerical improvements to the CIRA code

**Achievements**

CIRA computed the flow field around both geometries at two trajectory points using a two temperature model, i.e. the vibrational temperature differs from the rotational/translational temperature. Fig. 12 shows computed pressure and temperature contours in front of the larger model at flight trajectory point TP 1. Computed species mass concentration distribution along the stagnation point line for non-catalytic and equilibrium (or fully catalytic) surface conditions are plotted in Fig. 13. In the shock layer vibrational and rotational/translational temperatures differ significantly (Fig. 14).

The results of the work performed have been described in the SACOMAR deliverable D7.1 (CIRA Code Modelling Validation) [17].

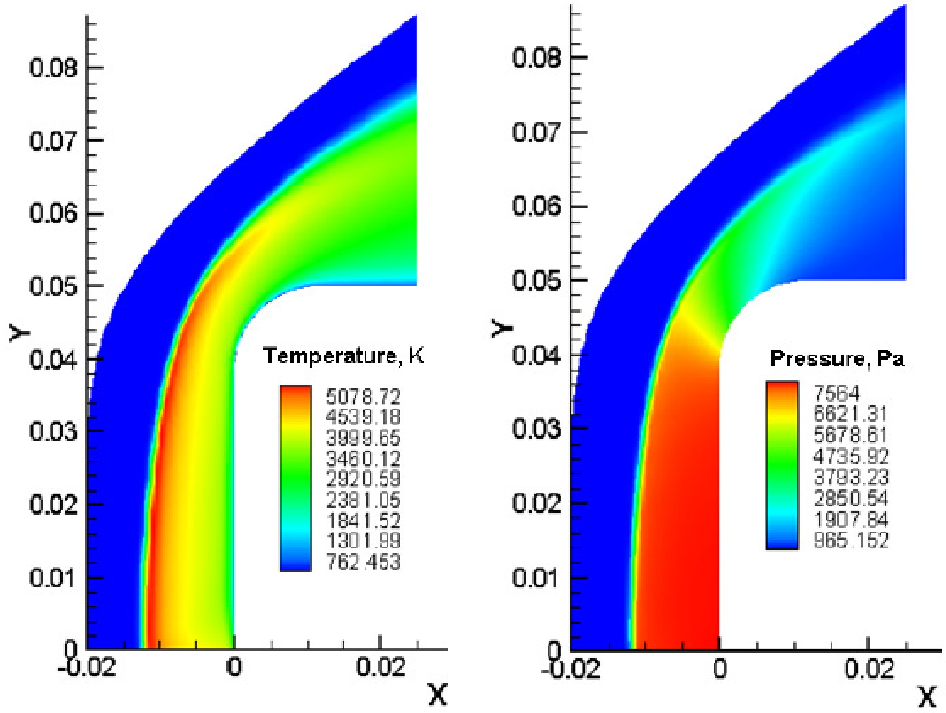



**Fig. 12: Pressure and temperature contours around the larger probe at TP 1 [17].**

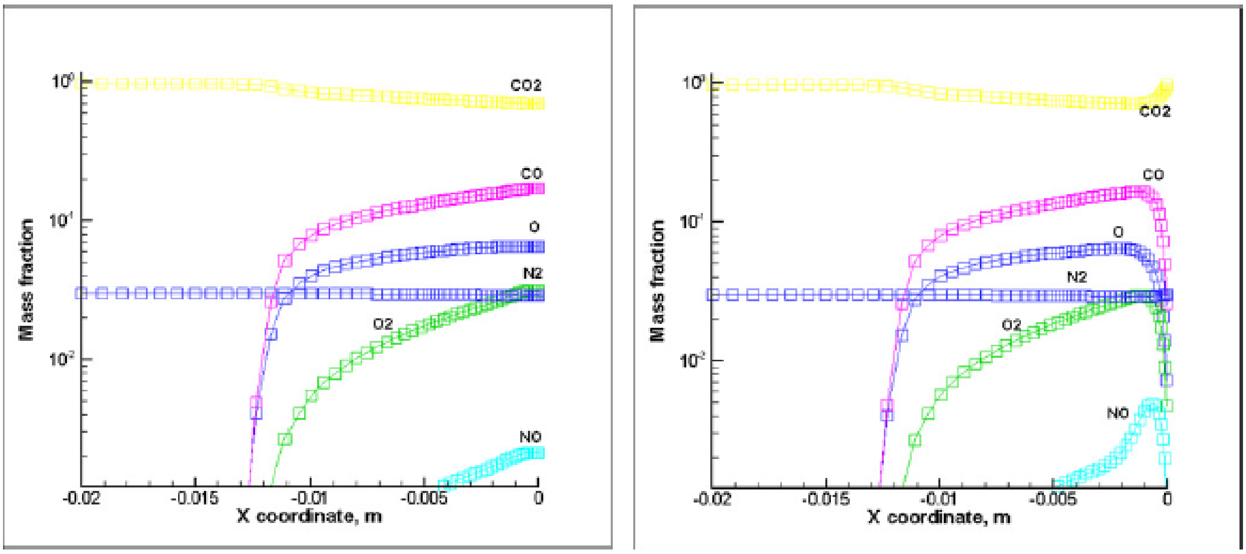
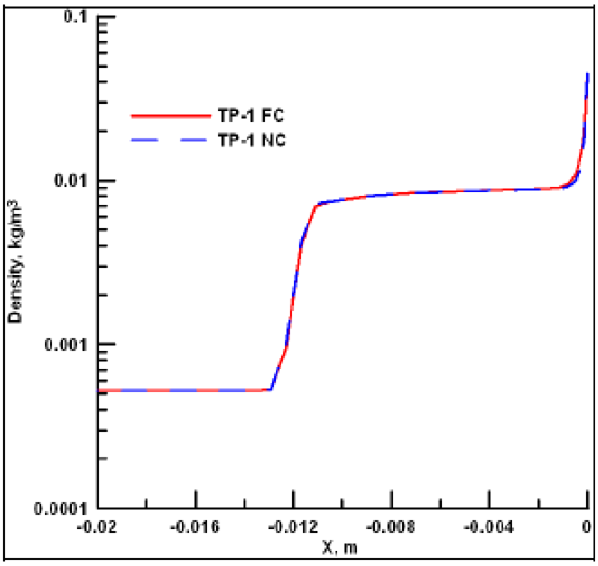



**Fig. 13: Species concentrations in the shock layer of the larger probe at TP 1, non-catalytic (left) and equilibrium (right) [17].**



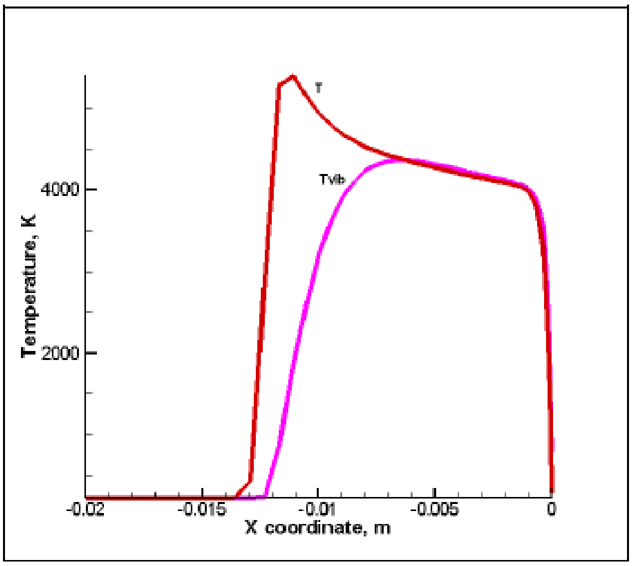




**Fig. 14: Density (left) and temperature (right) profiles along the stagnation line of the larger probe at TP 1 [17].**

## Task 7.2: TAU code modelling validation

**Responsible partner: DLR**

### Workplan according to DoW

- Implementation of modelling and numerical improvements to the TAU code.
- Validation of modelling and numerical improvements to the TAU code

### Achievements

The reaction scheme in the TAU code has been updated. It has been identified that the reaction involving nitrogen scatter significantly when comparing different data sources with each other [18]. Fig. 15 shows computed pressure contours including streamlines and mass concentration of species around the larger model at TP 1. Radial distribution of the heat flux rate for a non-catalytic and catalytic wall at TP 2 is shown in Fig. 16.

The results of the work performed have been described in the SACOMAR deliverable D7.3 (Improvement of TAU code with respect to the modeling and numerical scheme for $CO_2$+ $N_2$ flows) [18].

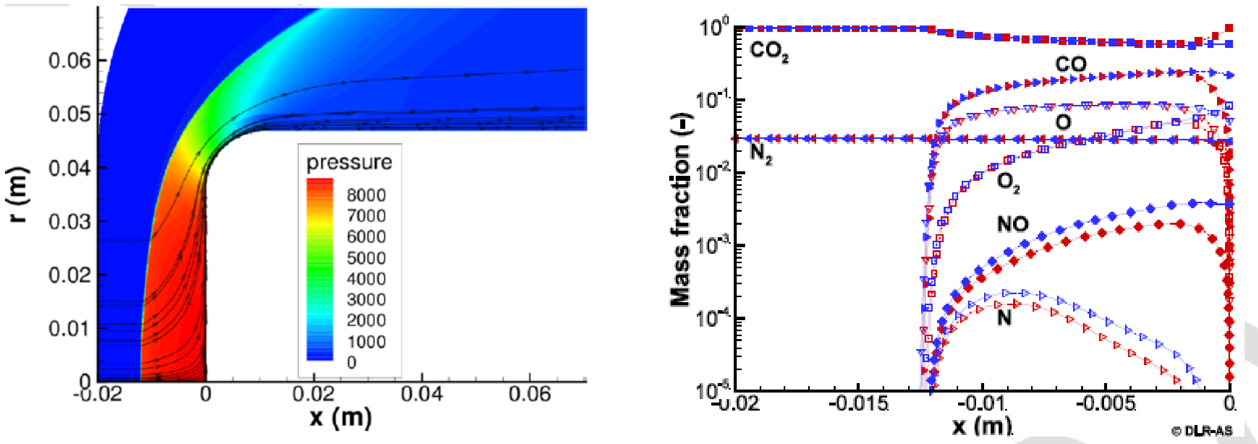



**Fig. 15: Pressure contours and streamlines (left) and mass concentration (right) for the larger probe at TP 1 [18].**

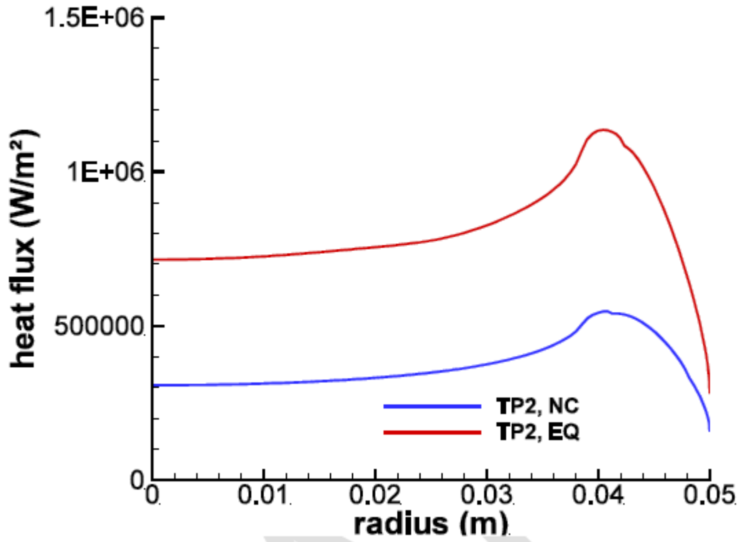



**Fig. 16: Computed heat flux distribution over the surface of the larger probe at TP 2 [18].**

## <u>Task 7.3: TsNIImash code modelling validation</u>

**Responsible partner: TsNIImash**

### Workplan according to DoW

This task has the following main objectives:

- Implementation of modelling and numerical improvements to the TsNIImash code.
- Validation of modelling and numerical improvements to the TsNIImash code

### Achievements

A robust numerical scheme for CO2 flows simulation was implemented into TsNIImash code. A significant effect of the thermal non-equilibrium on the aerothermal phenomena has been identified. At trajectory point TP 2 the vibrational non-equilibrium leads effects the temperature distribution in the shock layer significantly and leads to differences in the heat flux rate apprx. 20% (Fig. 17 Fig. 18 [19].

The results of the work performed have been described in the SACOMAR deliverable D7.5 (Improvement of the TsNIImash code with respect to the modeling and numerical scheme for $CO_2$+ $N_2$ flows) [19].

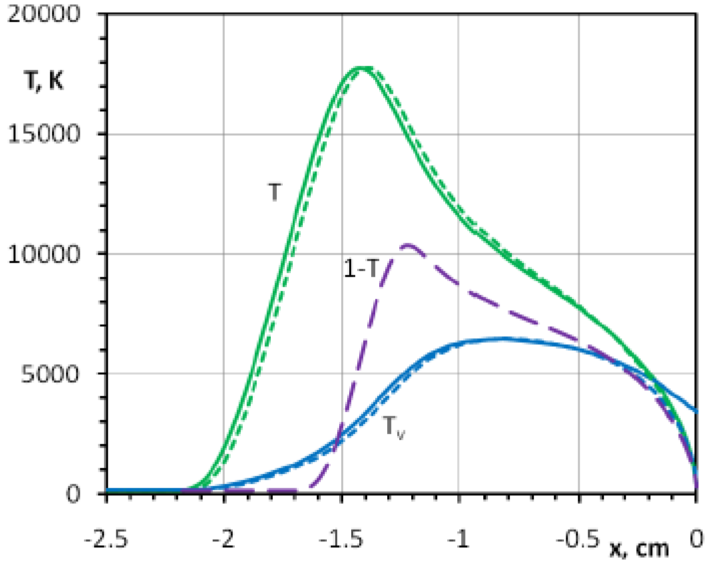



**Fig. 17: Temperature evolution along the stagnation line of a non-catalytic surface, larger model at TP 2 [19].**

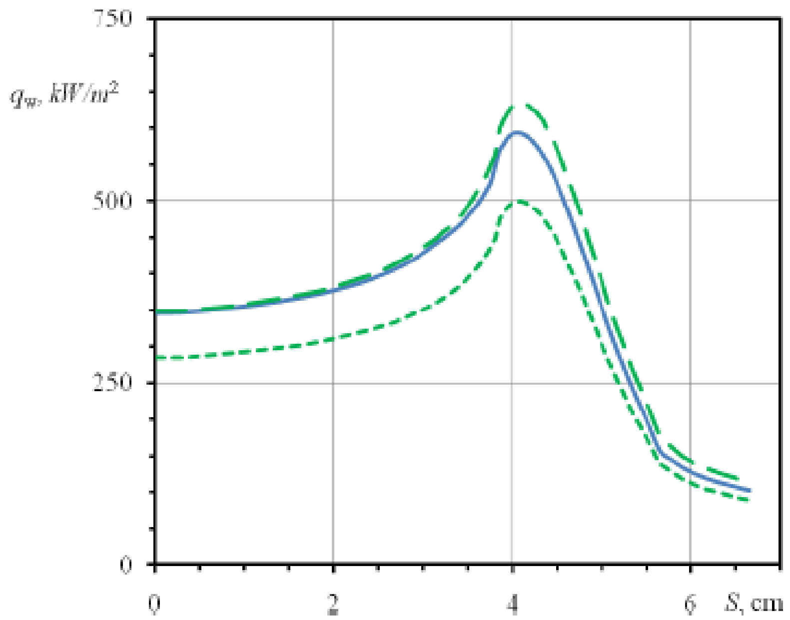



**Fig. 18: Heat flux distribution over the non-catalytic surface, larger model at TP 2 [19].**

## Task 7.4: ITAM code modelling validation

**Responsible partner: ITAM**

**Workplan according to DoW-**

- Implementation of robust numerical scheme for CO2 flows to the SMILE code.
- Implementation of modelling and numerical improvements to the ITAM code SMILE.
- Validation of modelling and numerical improvements to the ITAM code SMILE.

**Achievements**

Improvements aimed at SMILE computation speedup and robust numerical scheme for CO2 flows were implemented into the code. The CO2/N2 flow around a streamwise aligned cylinder with rounded edges was computed for conditions the DLR Cologne wind tunnel (Mach number 7.25 and Reynolds number 880). The translational temperature flowfield is presented in Fig. 19: . The DSMC simulation shows the significant difference between translational, rotational and vibrational temperatures clearly (**Fig. 20**).

The results of the work performed have been described in the SACOMAR deliverable D7.7 (Improvement of the TsNIImash code with respect to the modeling and numerical scheme for $CO_2$+ $N_2$ flows) [20].

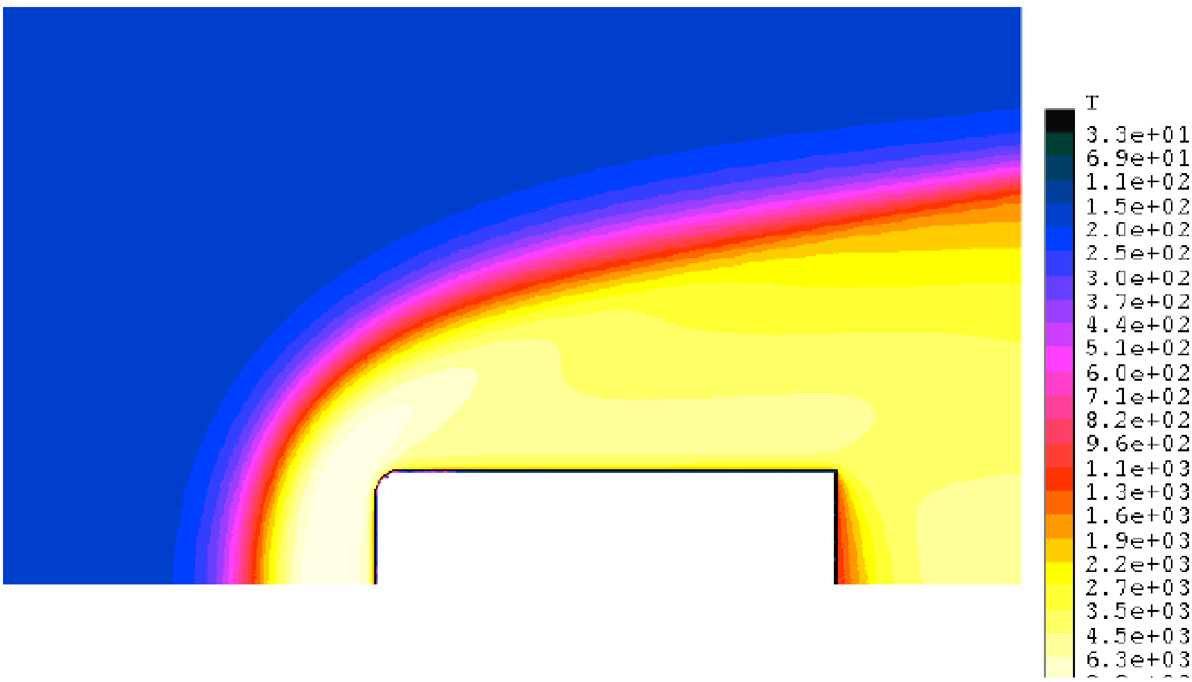



**Fig. 19: Translational temperature distribution (DSMC computation by the SMILE code) around the larger model at TP 2 [20] .**

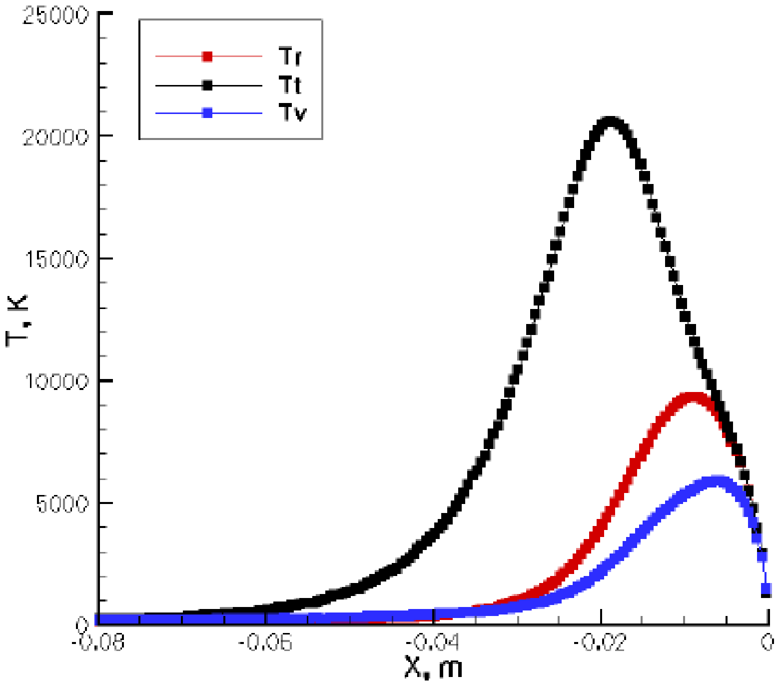



**Fig. 20: Evolution of translational, rotational and vibrational temperatures along the stagnation line of a non-catalytic surface, larger model at TP 2 [20].**

## <u>Task 7.5: Simulation of Shock Tunnel Tests</u>

**Responsible partner: ASTRIUM**

### Workplan according to DoW

- Numerical rebuilding of HEG experiments with the TAU code.
- Numerical rebuilding of IT-2 experiments with the TAU code.

### Achievements

TAU code was also used for the rebuiling of the experiments in the Shock Tunnel Göttingen HEG and Hot Shot Facility IT-2. As shown in Fig. 6, the agreement between computed and measured shock stand-off distance for the HEG test condition is quite good.

Fig. 21 refers to the **lp** case. As evident from the right diagram the pressure measurements generally agreed very well to CFD (within a few per cent with excellent agreement of stagnation point pressure for all test runs). In both cases **lp** (Fig. 21) and **hp** (Fig. 22) the measured surface heat flux rates are between the fully catalytic and the non-catalytic calculations as to be expected for the partially catalytic probe material (stainless steel). However, whereas for the **hp** condition the majority of the measurement values shown in Fig. 22 falls just slightly below the fully catalytic curve, for the **lp** condition the measurement values are situated at a distance below the fully catalytic calculation representing roughly one third of the difference between non-catalytic and fully catalytic calculations.

The **hp** experimental condition might therefore facilitate a more complete recombination at the probe than the **lp** condition. On the other hand an overall uncertainty of 10 % for HEG experimental heat flux measurements has been estimated by DLR and (even after implementing the modelling improvements worked out in the SACOMAR study into the TAU Code) there also still exists of course an uncertainty range of CFD results utilizing complex thermochemical modeling.

In any case a good predictive capability of the improved $CO_2$ thermochemical modeling developed within SACOMAR as now implemented in the TAU Code is confirmed by the comparisons to the HEG experimental data

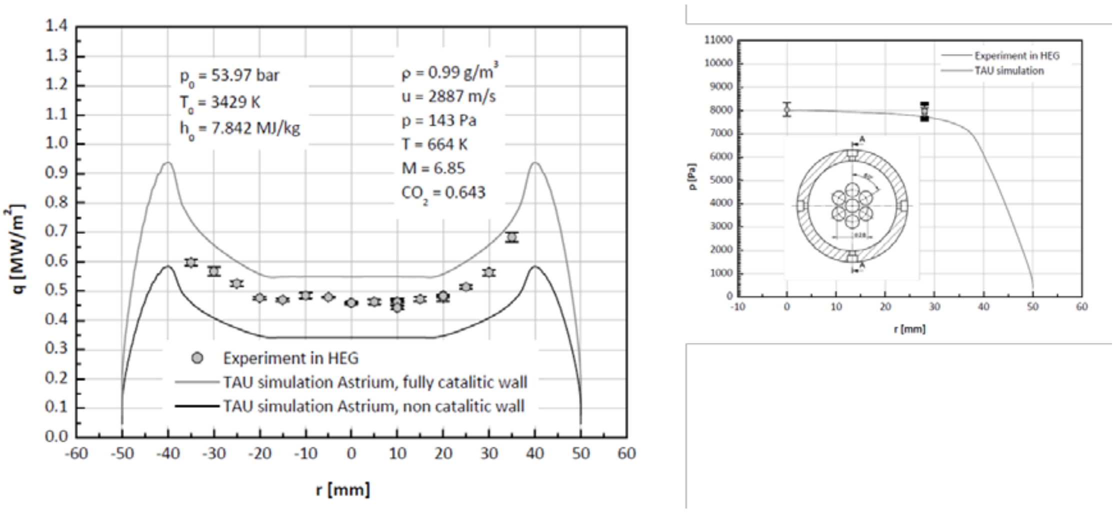



**Fig. 21: Comparison HEG Condition lp , Non Catalytic and Fully Catalytic Calculation vs. Test Results [8][21].**

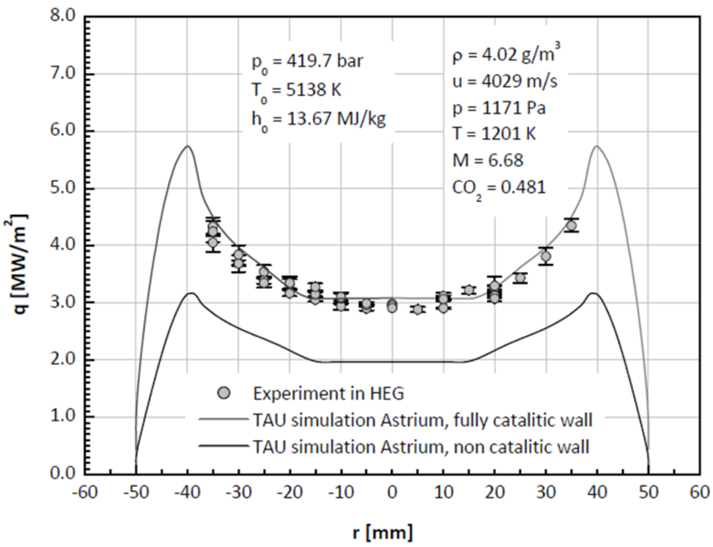



**Fig. 22: Comparison HEG Condition hp, Non Catalytic and Fully Catalytic Calculation vs. Test Results [8][21].**

As shown before in Fig. 7 the TAU Code CFD results (marked by "+" symbols ) predicts a trend consistent to the tests regarding reduced shock stand-off distance D for Regime 2 and Regime 3 compared to Regime 1. About ~ 2 mm offset of the shock stand-off distance between CFD and IT-2 tests again is possibly attributable to the single temperature model used in TAU (chemical non-equilibrium / thermal equilibrium model).

The results of the work performed have been described in the SACOMAR deliverable D7.9 (Numerical Simulation of HEG and IT-2 Experiments in $CO_2$ Flow) [21].

**Task 7.6: Simulation of IPG-4 Plasmatron Tests**

**Responsible partner: IPM**

**Workplan according to DoW**

This task has the following main objectives:

- Numerical rebuilding of the experiments in the IPM Plasmatron facility with the ALPHA, BETA and GAMMA codes.

**Achievements**

In order to rebuild the enthalpy and velocity in the subsonic free stream for the specified test conditions CFD modelling has been performed using ALPHA code for carbon dioxide plasma flows in the IPG-4 torch at different anode power, pressure and $CO_2$ mass flow rate. New grid geometry was constructed according geometry of the plasma torch with 40-mm-diam lengthened cylindrical nozzle. For the same input parameters and calculated profiles of all flow parameters at the plasmatron exit, subsonic dissociated carbon dioxide flow fields around a cooled test model were carried out by using code BETA for different distances from Plasmatron exit to model surface. Necessary flow parameters at the edge of boundary layer were calculated as well and have been used in Task 5.4 by GAMMA code with boundary conditions for fully catalytic wall to rebuild flow enthalpy and velocity in subsonic free stream.

Fig. 8 shows a summary of measured and calculated catalytic behaviour of different materials in the IPG-4 facility. It is clearly noticeable that the order of surface catalysis starting from most catalytic one is silver, copper, silver and quartz. The dashed lines of theoretical results describe calculated heat flux using the standard model. Solid lines show computed heat fluxes using the novel model, which is validated with the data of the SACOMAR project. The improvement is remarkable.

In addition IPM determined surface recombination coefficients using the standard catalysis model and the new novel catalysis model. The results are shown in Table 6.

The results of the work performed have been described in the SACOMAR deliverable D7.11 (Numerical simulation of IPG-4 experiments in $CO_2$+ $N_2$ flow) [22].

**Table 6: CO surface recombination coefficients determined using novel catalysis model [22]**

| P hPa | $N_{ap}$ kW | Zm mm | testing material | $T_w$ K | $q_w$ W/cm$^2$ | $\gamma_{wO}$ specified by literature data | $\gamma_{wCO}$ determined by novel model | $\gamma_w = \gamma_{wO} = \gamma_{wCO}$ determined previously by standard model |
|---|---|---|---|---|---|---|---|---|
| 80 | 40.4 | 40 | quartz | 755 | 70 | 2e–3 | 6.0e-3 | 7.84e-3 |
| | | | steel | 300 | 93 | 2.6e–3 | 6.1e-3 | 8.48e-3 |
| 80 | 34.0 | 40 | quartz | 600 | 45 | 2e–3 | 3e-3 | 4.97e-3 |
| | | | steel | 300 | 66 | 2.6e–3 | n/a | 1.07e-2 |
| 40 | 35.0 | 72 | quartz | 606 | 46 | 2e–3 | 5e-3 | 5.71e-3 |
| | | | steel | 300 | 72 | 2.6e–3 | 9e-3 | 1.13e-2 |
| 40 | 35.0 | 122 | quartz | 500 | 30 | 2e–3 | 2e-3 | 3.42e-3 |
| | | | steel | 300 | 45 | 2.6e–3 | 7e-3 | 8.77e-3 |

## Task 7.7: Simulation of U13 Plasmatron Tests

**Responsible partner: TsNIImash**

### Workplan according to DoW

The objective of this task is numerical rebuilding of the experiments in the TsNIImash Plasmatron facility with the TsNIImash code.

### Achievements

A dedicated study concerning the catalytic effects on the heat flux rate has been carried out by TsNIImash. TsNIImash performed tests on different catalytic surfaces, i.e. silver, copper and steel. The rebuilding of this tests shows that the final finishing of the silver surface or oxidation process has an important effect on the surface catalysis [23]. Copper surface has a comparable catalycity like electrolyte silver used for the tests (see Fig. 9). The quartz surface seems to be low catalytic.

TsNIImash simulation showed that compared to the gas kinetics and transport properties the surface catalysis is the main contributor to the heat transfer (**Fig. 23**).

The results of the work performed have been described in the SACOMAR deliverable D7.13 (Numerical simulation of experiments in the TsNIImash Plasmatron facility) [23].

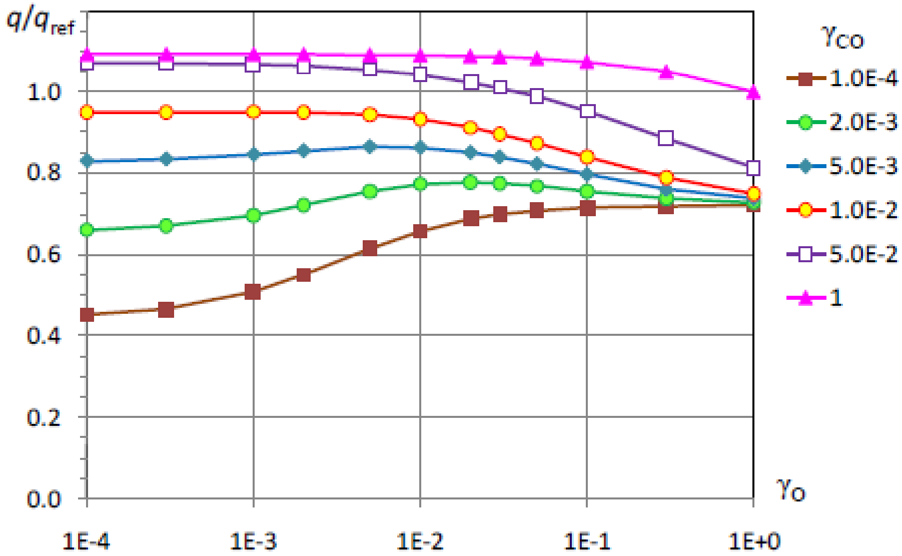



**Fig. 23: Relative stagnation point heat flux rate for different recombination probabilities [23].**

## Task 7.8: Simulation of Arcjet Tests in L2K

**Responsible partner: CIRA**

**Workplan according to DoW**

- Numerical rebuilding of L2K experiments with the CIRA code.

### Achievements

Experiments in the L2K facility were simulated by CIRA using the Fluent code with two temperature model. In order to determine the thermal non-equilibrium effects effects strong attention was paid also to the flow characterization using novel measurement techniques [24]. As shown in **Fig. 24** the agreement between measured and computed Pitot pressure profiles at FC-I of the L2K facility is good. The situation is similar for the FC-II.

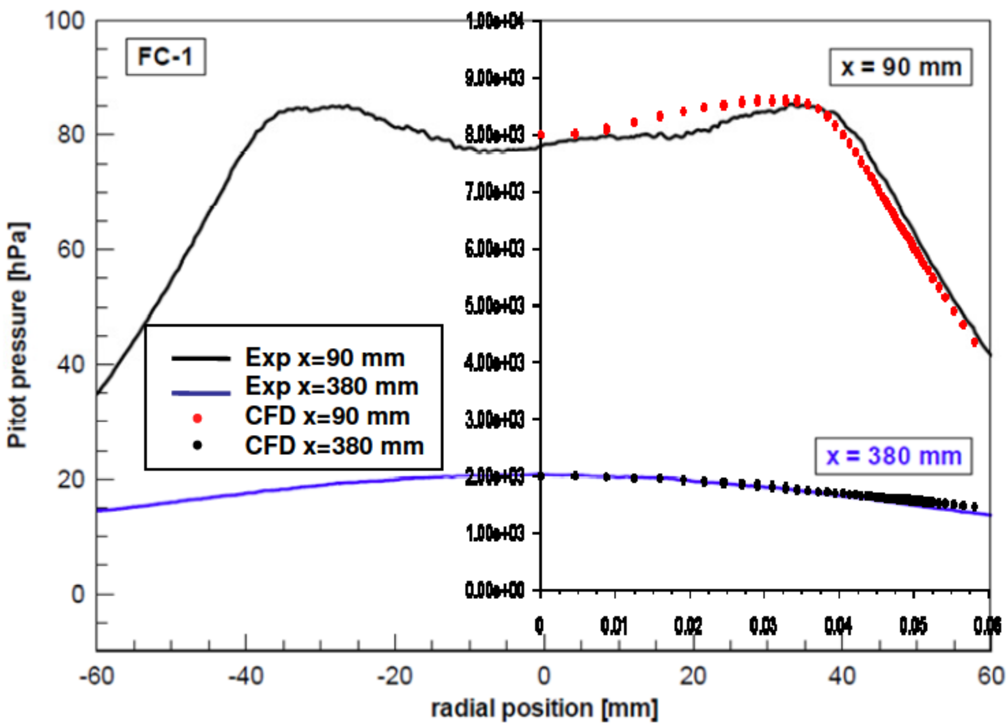



**Fig. 24: Measured and computed Pitot pressures for FC-I conditions in L2K [21] [24].**

For the measurement of the vibrational and rotational temperature of NO molecules Laser Induced Fluorescence (LIF) technique has been used. **Fig. 25** shows measured rotational temperature profiles, which are assumed being equal to the translational temperature, in comparison with calculated temperature. The agreement is not so good as the Pitot pressure. This is probably related to using one vibrational temperature for all species.

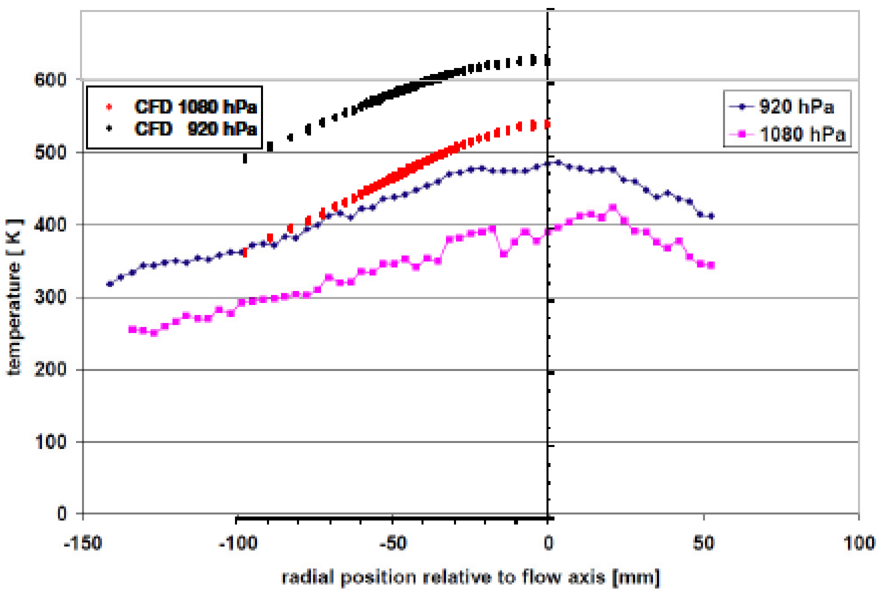



**Fig. 25: Measured and computed free stream temperature profiles for both FC-I and FC-II flow conditions in L2K [12][24].**

A further very interesting data is the comparison between measured and calculated temperature beyond the bow shock with LIF (Fig. 26). Here the agreement seems to be good. But it has to be mentioned the inaccuracy of measured temperature is more than 8%. At the same time the total temperature is similar to the Pitot pressure less sensitive to the non-equilibrium effects in the free stream.

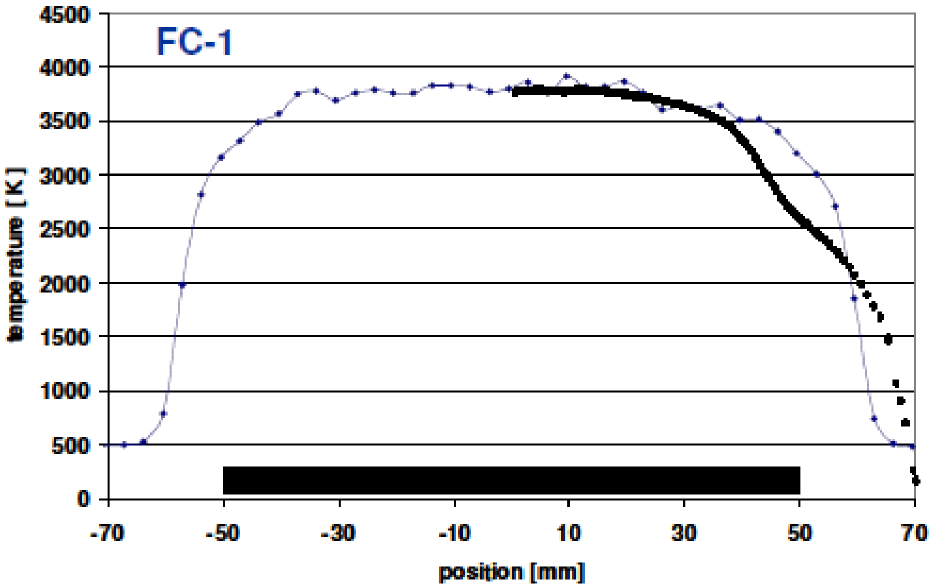



**Fig. 26: Measured and computed temperature profiles in the shock layer 6 mm from the surface of the model with 100 mm diameter at 380 mm from the nozzle exit and FC-1 [12][24].**

Finally the cumulative effect of all these parameters should be seen on the heat flux rate. At L2K conditions the heat flux to the HFM sensor is always the highest and can be considered the fully catalytic heat flux rate. As shown in **Table 7** the heat flux value measured with the HFM sensor is quite close to the calculated fully catalytic heat flux. Other two surfaces (steel and copper) seem to be partial catalytic. For the interpretation of these results it has to be considered that the heat flux sensors have an uncertainty in the order of 10% to 15%. Again the CFD computations have the highest uncertainty for in heat flux calculation. The results of the work performed have been described in the SACOMAR deliverable D7.15 (Simulation of L2K Tests) [24].

**Table 7: Measured and computed heat fluxes in L2K [12][24]**

| Test condition | Model diameter | Pressure [Pa] | | | | Heat flux rate [kW/m²] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | [mm] | Pitot pressure | CFD Pitot | S.P. pressure | CFD p02 | HFM sensor | Slug (stainless steel) | Water-cooled (copper) | CFD FC | CFD NC |
| FC-1 | 100 | 21.6 | 20 | - | 20.3 | 891 | 640 | - | 820 | 260 |
| | 50 | 21.6 | 20 | 21.9 | 19.4 | 1091 | 740 | 830 | 1100 | 360 |
| | 50 | 77.5 | 80 | 80.1 | 80.9 | - | 1380 | 1680 | 1800 | 580 |
| FC-2 | 100 | 18.5 | 18 | - | 16.2 | 518 | 355 | - | 500 | 190 |
| | 50 | 18.5 | 18 | 19.3 | 15.5 | 694 | 440 | 570 | 660 | 260 |
| | 50 | 67.6 | 72 | 69.8 | 69.6 | - | 630 | 1000 | 1200 | 500 |

## 3.3 Project Management

All milestones of the project have been achieved. The project costs stayed within the available budget.

For the presentation of the project and information exchange with the project partner and European scientific community, a ftp server (sacomar@ftp.dlr.de) and a project portal on the web-site (www.dlr.de/as/sacomar) has been established.

Besides several teleconferences and intensive e-mail exchange, following meetings were organized:

| Meeting | Location | Date |
|---|---|---|
| Kick.-off | Cologne, Germany | 20./21.01.2011 |
| Progress Meeting | Kovalev, Russia | 10./11.10.2011 |
| Final Technical Meeting | Torino, Italy | 28./29.06.2012 |

There were no changes to the legal status of any of the beneficiaries. The project did not have any sub-contractors.

## 4 References

[1] Gülhan, A., et al; SACOMAR Interim Progress Report, SACOMAR Deliverable D1.1, issue 1.0 16.12.2011.

[2] Mareschi, V.; Requirements on Modelling and Simulation, SACOMAR deliverable D 4.1, issue 1.1, 30.10.2011.

[3] Mareschi, V.; Synthesis of Results, SACOMAR deliverable D 4.2, issue 1.0, 31.07.2012.

[4] B. Esser., A. Gülhan; Test plan for Experiments, SACOMAR deliverable D 5.1, 30.6.2011.

[5] P. Nöding; Review of $CO_2$ Physico-Chemical Modelling and Recommendation for Improvement, SACOMAR deliverable D 6.1, Issue 1.1, 30.11.2011.

[6] Steven Sepka Yih-Kanq Chen and Jochen Marschall and Richard A. Copeland, 'Experimental Investigation of Surface Reactions in Carbon Monoxide and Oxygen Mixtures', Journal of Thermophysics and Heat, Vol. 14, No. 1, January–March 2000.

[7] Jochen Marschalll and Richard A. Copeland, Helen H. Hwang and Michael J. Wright, 'Surface catalysis experiments on metal surfaces in Oxygen and Carbon Monoxide Mixture', AIAA paper 2006-181.

[8] J. Martinez Schramm: Results of Experimental Study in the High Enthalpy Shock Tunnel Göttingen (HEG), SACOMAR Deliverable D 5.2, Issue 1.0, 21.02.2012.

[9] V.Ya. Borovoy, A.S. Skuratov, I.V. Struminskaya, E.G. Zaitsev; TsAGI Deliverable 5.3, Results of experimental study in TsAGI IT-2 Hot Shot wind tunnel, 27.02.2012.

[10] A. Koleshnikov, A. Gordeev, S. Vasilevski; Results of the experimental study in the IPG-4 facility, SACOMAR Deliverable D5.4, Issue 2.1, 30.09.2011.

[11] R. V. Kovalev, V. I. Vlasov; N. F. Rudin, G. N. Zaloginn; Results of experimental study in the TsNIImash Plasmatron Facility U-13, SACOMAR Deliverable D5.5, Issue 1.0, 30.09.2011.

[12] B. Esser, U. Koch, A. Gülhan.; Results of the experimental study in the L2K Facility, SACOMAR Deliverable D5.6, Issue 1.1, 30.06.2012.

[13] P. Nöding; Review of Physico-Chemical $CO_2$ Modelling and Recommendation for Improvements, SACOMAR Deliverable D6.1, Issue 1.1, 30.11.2011.

[14] R. V. Kovalev, V. I. Vlasov; G. N. Zaloginn; Modelling of $CO_2$+$N_2$ gas mixture, SACOMAR Deliverable D6.2, Issue 1.0, 30.01.2012.

[15] M. Fertig; Report and library on gas phase chemistry, SACOMAR Deliverable D6.3, Issue 1.0, 10.02.2012.

[16] A. Koleshnikov, S. Vasilevski, A. Gordeev, A. Levitin; Reprot and library on surface chemistry, SACOMAR Deliverable D6.4, Issue 1.0, 26.01.2012.

[17] Mario De Stefano Fumo; CIRA Code Modelling Validation, SACOMAR Deliverable D7.1, Issue 1.0, 14.07.2012.

[18] M. Fertig; Improvement of TAU code with respect to the modeling and numerical scheme for $CO_2$+ $N_2$ flows, SACOMAR Deliverable D7.3, Issue 1.0, 31.07.2012.

[19] R. V. Kovalev, A. G. Gorschkov, V. I. Vlasov; Improvement of the TsNIImash code with respect to the modeling and numerical scheme for $CO_2$+ $N_2$ flows, SACOMAR Deliverable D7.5, Issue 1.0, 30.03.2012.

[20] Ye. A. Bonder, M. S. Ivanov; Improvement of the TsNIImash code with respect to the modeling and numerical scheme for $CO_2$+ $N_2$ flows, SACOMAR Deliverable D7.7, Issue 1.0, 23.06.2012.

[21] P. Nöding; Numerical Simulation of HEG and IT-2 Experiments in $CO_2$ Flow, SACOMAR Deliverable 7.9, 15th August 2012.

[22] A. Koleshnikov, A. Gordeev, S. Vasilevski; Numerical simulation of IPG-4 experiments in $CO_2$+ $N_2$ flow, SACOMAR Deliverable D7.11, Issue 1.0, 20.03.2012.

[23] R. V. Kovalev, A. B. Gorshkov, V. I. Vlasov; Numerical simulation of experiments in the TsNIImash Plasmatron facility, SACOMAR Deliverable D7.13, Issue 1.0, 30.05.2012.

[24] Mario De Stefano Fumo; Simulation of L2K Tests, SACOMAR Deliverable D7.15, Issue 1.0, 14.07.2012.