# Technical approach and validation of reentry heating simulation for the Pre-X and EXPERT vehicles using the IPG-4 plasmatron

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## Abstract
The results of the stagnation point heating simulation for the Pre-X and EXPERT vehicles using the capabilities of the 100-kW IPG-4 plasmatron are presented. The two different technical approaches based on the LHTS concept to expand the IPG-4 capabilities at the low pressure & high enthalpy and high pressure & low enthalpy are developed. Catalytic efficiency of the reference sintered SiC material with respect to heterogeneous recombination of the atomic oxygen and nitrogen are predicted for the reentry conditions of both above vehicles through multiparameter heat transfer modeling and comparison with data of stagnation point heat transfer rates.

## 1. Introduction

It is generally accepted to perform aerothermal tests and predict TPM surface catalycity with respect to atomic oxygen and nitrogen recombination in high-enthalpy air flows at the specified stagnation pressure and surface temperature. On this traditional way it is always difficult to find an accurate correlation between ground test and reentry flight conditions.

The 100-kW IPG-4 plasmatron[1,2] has been widely used for simulation of the thermochemical interaction of high-enthalpy air and $CO_2$ flows with thermal protection materials (TPM) under different Earth and Mars atmospheric entry conditions. In this paper we use our Local Heat Transfer Simulation (LHTS) concept[1,3,4] as the basic methodology for the planning the high-enthalpy air tests in the IPG-4. In this way the correlation between the free stream conditions in plasmatron, trajectory parameters and geometry of the test model and the nose radius of the vehicle are established. Extended capabilities of the IPG-4 plasmatron and the LHTS methodology are supported by sufficient diagnostics and CFD modeling of the flow field and heat transfer for the test conditions reveal a novel approach for aerothermal ground testing and predicting TPM catalycity for the Pre-X and EXPERT reentry conditions.

## 2. LHTS concept

The LHTS concept[1,3,4] requires that the three key parameters - the total enthalpy $H_\infty$, stagnation pressure $p_0$ and velocity gradient $\beta_0$, which control the stagnation point heat transfer[5], - have to be equal in hypersonic flight and ground high-enthalpy test:

$$H_{2e}= H_{1e}= H_\infty,\quad p_{20}= p_{10w},\beta_{20}=\beta_{10} \qquad \textbf{(1)}$$

Here subscripts *1* and *2* denote the flight and test conditions, *e* - the edge of the boundary layer, *w* - the wall. If the flows in free flight and ground facility outside of the boundary layers are under equilibrium, above requirements provide the similarity of the nonequilibrium boundary layers and heat transfer at the stagnation point. The LHTS concept has been validated for the high-enthalpy subsonic flows of nitrogen[6] , carbon dioxide[7] and air[8].

We assume that the free stream velocity $V_{1\infty}$, static pressure $p_{1\infty}$, density $\rho_{1\infty}$ and geometry of a vehicle and model are given. If we introduce the scaling factors ξ and ζ as follows

$$\xi = \frac{R_m^*}{R_b^*},\quad \zeta^2 = \frac{V_{1\infty}^2}{2H_\infty}\xi^2,\quad R_w^* = V_{1\infty}/\beta_{01},\quad R_m^* = V_{2\infty}/\beta_{02} \qquad \textbf{(2)}$$

the correlation between the subsonic free stream parameters in plasmatron and hypersonic free flight conditions becomes the form

$$V_{2\infty} = \xi V_{1\infty} \qquad \textbf{(3)}$$

$$h_{2\infty} = \frac{1}{2}V_{1\infty}^2 \qquad \textbf{(4)}$$

$$p_{2\infty} = (1-k_1)\rho_{1\infty}V_{1\infty}^2 \qquad \textbf{(5)}$$

In this case the effective radius of a blunt nose in hypersonic flow can be expressed as follows[9]

$$R_N^* = \left(\frac{8}{3}k_1\right)^{-1/2} R_N \qquad \textbf{(6)}$$

Finally, Eq. (3) becomes the form

$$V_s = \left(\frac{8}{3}k_1\right)^{1/2} \frac{R_m^*}{R_N} V_{1\infty} \qquad \textbf{(7)}$$

## 2. Similarity of the Pre-X stagnation point heating

For the further analysis we take into account, that subsonic flow at the ICP torch exit is non-uniform and downstream parameters depend on the distance from the exit $L$. We consider the parameters $p_s$, $V_s$ and $h_s$ at the center of the discharge channel exit as the characteristic ones. For that case it is convenient to express the velocity gradient and enthalpy at the edge of the test model boundary layer as

$$\frac{V_S}{R_m^*} = \frac{V_S}{R_m}\alpha\left(R_m, R_C, L, N_{pl}, G\right) = \left(\frac{8}{3}k_1\right)^{1/2}\frac{V_\infty}{R_N} \qquad \textbf{(8)}$$

$$h_{2e} = h_S\varphi\left(R_m, R_C, L, N_{pl}, G\right) = \frac{V_\infty^2}{2} \qquad \textbf{(9)}$$

If the mass flow rate $G$ is constant, only $p_s$ and $h_s$ are independent, and $V_s$ is the function of these parameters. When the ICP fire ball exists in the optimal regime, the correlation for above parameters can be approximated in the form

$$p_S V_S = p_* V_* \chi\left(h_S/h_*, N_{pl}, Q\right) \qquad \textbf{(10)}$$

where $p_*$, $V_*$ and $h_*$ are some reference values, and the function $\chi(h_s/h_*, N_{pl}, G)$ is specific one for an ICP torch. The determining this characteristic function has appeared to be quite important task of the experimental and numerical characterization of any inductively heated facility in terms of duplicating reentry heating.
Equations (8) – (10) were used in order to find the correlation between parameters $p_w$ and $H_\infty$ as follows

$$\frac{p_w}{p_*} = \left(\frac{8}{3}k_1\right)^{-1/2}\alpha\frac{R_N}{R_m}\chi\left(\frac{H_\infty/\varphi}{h_*}, G\right)\frac{V_*}{\sqrt{2H_\infty}} \qquad \textbf{(11)}$$

If the reentry trajectory is expressed as

$$p_w = F(H_\infty) \qquad \textbf{(12)}$$

in the plane $p_w$-$H_\infty$ we can find the intersection point of the curves given by Eqs. (11) and (12), if this intersection point exists. At this trajectory point all the three reentry parameters $H_\infty$, $p_w$ and $\beta_{01}$ can be duplicated simultaneously in subsonic high-enthalpy flow.

Let us apply this methodology in order to find the point of the Pre-X trajectory, where the complete local duplication of the stagnation point heating by the IPG-4 plasmatron is possible. To do that, we will use the four trajectory points of the Pre-X[10] and the data of diagnostics and CFD modeling the three subsonic air test regimes selected and realized for partial duplication of the stagnation point heat flux[11].

Table 1: Pre-X reentry conditions

| Pre-X trajectory point | Velocity (m/s) | Stagnation pressure (Pa) |
|---|---|---|
| 1 | 7650 | 414 |
| 2 | 7621 | 1062 |
| 3 | 6657 | 3748 |
| 4 | 5584 | 7607 |

Table 2: IPG-4 subsonic free stream conditions

| IPG-4 air test regime | Pressure $p_S$ (hPa) | Enthalpy $h_S$ (MJ/kg) | Velocity $V_S$ (m/s) |
|---|---|---|---|
| 1 | 20 | 33 | 690 |
| 2 | 38 | 36.5 | 395 |
| 3 | 78 | 30 | 145 |

Using the parameters of the regimes 2 and 3 we approximate the correlation (10) as

$$p_S V_S = p_{S3} V_{S3} \left(1.51 h_S / h_{S3} - 0.51\right)$$

Because the Pre-X vehicle has the nose radius $R_N$ = 0.925 m, the stagnation point configuration of the test with a 140-mm diameter flat face model was chosen as the optimal one. For above free stream conditions at $L$ = 100 mm, $R_m$ = 70 mm using Alpha and Betha codes[12] we have found $\alpha$ = 1.2, $\varphi$ = 0.73.

In Fig. 1 in the coordinate $p_w$-$H_\infty$ possible Pre-X trajectory[10] is shown by the curve 1, the curve 2 presents Eq. (11). This curve crosses the Pre-X trajectory in the single point $H_\infty$ = 18.75 MJ/kg, $p_w$ = 5800 Pa ($V_\infty$ = 6120 m/s, Z = 65.4 km). The stagnation point heat flux for this trajectory point can be duplicated at the corresponding IPG-4 test parameters $H_S$ = 25.7 MJ/kg, $p_S$ = 5800 Pa. Actually, these heat transfer conditions are close to the peak-heating point.

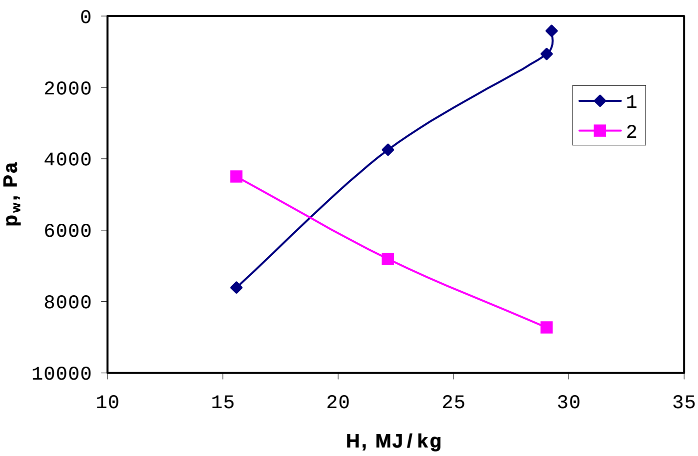


Figure 1: Pre-X re-entry trajectory (curve 1) and trajectory point for complete simulation of stagnation point heating. Curve 2 – Eq. (11)

To provide the optimal test configuration for the duplicating stagnation point heating, the new testing model was developed and manufactured on the basis of a full scale (150×150×50 mm) light-weight Silica-based thermal protection tile. The tests of the newly developed model equipped with the SiC sample (samples made of sintered SiC were provided by Dr. Marianne Balat-Pichelin, PROMES/CNRS) in subsonic high-enthalpy air flows were performed in stagnation point configuration under test conditions 1, 2 and 3. The temperature of the SiC sample surface was measured by a pyrometer with the disappearing filament. The heat losses from the backside of the SiC sample were practically negligible due to exceptionally low thermal conductivity of the Silica-based thermal insulation material (less than 1% at the steady state surface temperature 1250°C). The reference full-scale thermal protection tile without SiC sample was tested in the same regimes to obtain the reference surface temperatures.

In Fig. 2 the comparison of calculated surface temperature for the fully catalytic radiative equilibrium wall at the Pre-X re-entry conditions (upper curve) and measured temperatures of the SiC samples (rhombs) and Silica-based coating (circles) is given. The test point 2 is the nearest to the peak-heating point and to the test regime for the complete local simulation of the stagnation point heat flux. We see that the IPG-4 plasmatron tests predict the decrease of the Pre-X stagnation point temperature on 300-350 K with respect to fully catalytic wall at the peak heating part of the trajectory, if SiC material is used. Conditions (8) and (9) are not satisfied for the test regime 3, therefore SiC and Silica-based surface temperatures are overestimated at this point. Due to low difference between surface temperatures, catalycity of SiC material appears to be a little bit higher that catalycity of the borocilicate coating.

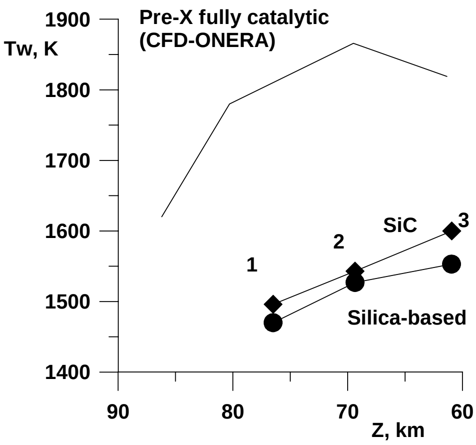


Figure 2: Stagnation point temperature of the Pre-X vehicle (fully catalytic surface), temperature of SiC and Silica-based surfaces under the IPG-4 plasmatron air test regimes 1 – 3

## 3. Predicting SiC catalycity for the Pre-X reentry conditions

According to IPM approach, numerical study of the heat transfer and predicting SiC catalycity were carried out through the three stages:

1) Calculation of equilibrium air ICP flow in IPG-4 discharge channel (torch) by Alpha code based on numerical solution of Navier-Stokes equations and 1D equation for the averaged amplitude of the high-frequency electric field;

2)Calculation of the equilibrium high-enthalpy air flow over the testing model in the IPG-4 test chamber and determination of the set of dimensionless parameters at the external edge of boundary layer at the model front surface (Beta code);

3) Calculation of the nonequilibrium air boundary layer and heat transfer at the stagnation line near the model front surface, rebuilding free stream conditions and determination of surface catalycity of the testing material (Gamma code). The previously obtained dimensionless parameters were used here to account for the boundary layer thickness and flow vorticity.

The main result of the 1-st and 2-nd stages is the set of dimensionless parameters to be used in the 3-rd stage. Flow enthalpy, temperature and other parameters obtained in result of the Alpha and Beta code calculations are not used in further boundary layer calculations and catalycity determination.

The simple model of heterogeneous reactions is used together with the assumption that efficiencies of surface recombination of O and N atoms are equal, $\gamma_{wO} = \gamma_{wN} = \gamma_w$, and at the surface there is not production of NO molecules. The results of rebuilding the subsonic air free stream conditions obtained by the nonequilibrium boundary layer calculations with use of experimental data of stagnation point heat flux and dynamic pressure are shown in the Table 3. Here $h_e$, $T_e$ are the flow enthalpy and temperature at the boundary layer edge, $V_0$ is the reference flow velocity at the center of the torch exit section.

Table 3: Rebuilt air test conditions

| IPG-4 regime | $h_e$, MJ/kg | $T_e$, K | $V_0$, m/s |
|---|---|---|---|
| 1 | 14.0 | 5033 | 676.6 |
| 2 | 15.3 | 5275 | 336.8 |
| 3 | 15.95 | 5490 | 112.1 |
| 3E | 14.75 | 5377 | 78.3 |

In calculations carried out here, enthalpy $h_e$ was determined by the measured value of $q_{wc}$ - the stagnation point heat flux to the cooled copper surface under assumption that the copper surface is fully catalytic one.
The heat flux envelope determined by the boundary layer calculations for the air flow regime 2 is shown in Fig. 3. The stagnation point heat flux for the non-catalytic wall ($\gamma_w$=0) is shown by the lower curve. Symbols correspond to measured values of the heat flux to the water cooled copper model and to the SiC material and Silica-based tile.

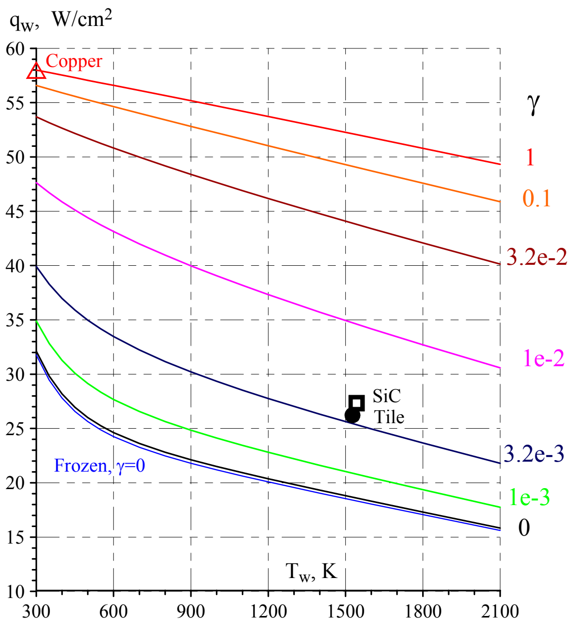


Figure 3: Heat flux envelope for the Pre-X test regime 2: $Z_m$=130 mm, $P_0$=38 hPa, $N_{pl}$=30.7 kW. Measured heat fluxes to testing materials are shown by the symbols

## 4. IPG-4 subsonic air tests for the EXPERT vehicle

The prior analysis[11] based on the LHTS concept has shown that the IPG-4 plasmatron is capable to duplicate stagnation point heating of the EXPERT vehicle[13] at the arbitrary TPM catalycity using 50-mm diameter Euromodel. The EXPERT trajectory points specified by ESA are given in the Table 4.

Table 4: EXPERT reentry conditions

| EXPERT trajectory point | Altitude, km | Velocity, m/s | Stagnation pressure, Pa | Heat flux, W/cm$^2$ ($\gamma_w$=1) |
|---|---|---|---|---|
| 1 | 52.6 | 4997 | 17100 | 77 |
| 2 | 43 | 4834 | 53700 | 133.5 |
| 3 | 34 | 4253 | 167800 | 179 |

In contrast to the Pre-X reentry conditions, the EXPERT peak heating part of the trajectory occurs at high pressure and low enthalpy (low altitude). Hypersonic flow conditions specified at the Table 4 are close to the border of the IPG-4 operating envelope in terms of enthalpy and pressure. In fact, the point 3 is out of the IPG-4 operating envelope. The maximum pressure available for testing TPM materials is about $10^5$ Pa, but at this pressure velocity of the air plasma flow is very low and velocity gradient at the stagnation point of the model is much less, than at the EXPERT flight conditions. In subsonic flow we can sufficiently change the enthalpy at the edge of the boundary layer by varying the distance from the plasmatron exit section to the model, but if this distance is long enough, the quality of the subsonic free stream conditions are not sufficient for the catalycity tests. In order to approach to the EXPERT reentry conditions and to improve quality of the free stream conditions it is necessary to increase the velocity of the subsonic flow. The required velocity $V_s$ can be estimated from the relation as follows

$$\left(\frac{8}{3}k\right)^{1/2}\frac{V_\infty}{R_N}\approx 0.78\frac{V_S}{R_m}$$

In the case $R_N$ = 0.55 m, $V_\infty$ = 5000 m/s, $R_m$ = 0.025 m we have found $V_s \approx$ 120 m/s. At high pressure that velocity can be provided in subsonic regime using a sonic nozzle with a throat diameter 40 mm. Such nozzle is in the list of the instrumentation developed and manufactured at IPM for the IPG-4 plasmatron. It was decided to use the sectional nozzle with a conical part and a cylindrical part with inner diameter 40 mm. Fig. 4 shows high quality subsonic jet after cylindrical nozzle. Finally, two cylindrical sections of the 40 and 80 mm length were developed, manufactured and used in aerothermal air tests. In such test configuration the calculated stagnation pressure and fully catalytic stagnation point heat fluxes specified by ESA (the Table 4) can be realized.

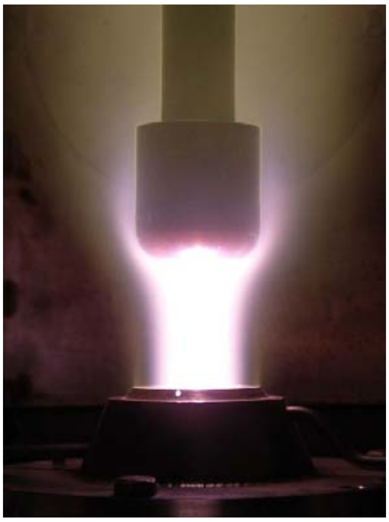

Figure 4: Stagnation point test configuration with precompression of subsonic high-enthalpy air flow at the plasmatron exit using water-cooled conical nozzle with 40-mm diameter throat

SiC sample mounted in a euromodel made of SiC was exposed in subsonic air flow and tested in the same stagnation point configuration at the pressure p = 170 hPa, anode power $N_{ap}$ = 25 kW, mass flow rate G = 2.4 g/s, dynamic pressure $\Delta p$ = 166 Pa, fully catalytic heat flux (cooled copper) $q_{fc}$ = 77 W/cm$^2$. SiC surface measured by pyrometry was $T_w$ = 1650 K, stagnation point heat flux was rebuilt as $q_w = \varepsilon\sigma T_w^4 + q_{loss}$ (=38.3 W/cm$^2$), where $\varepsilon$ (=0.85) – surface emissivity, $\sigma$ - the Stefan-Boltzmann constant, $q_{loss}$ – measured heat losses.

## 5. Predicting SiC catalycity for the EXPERT reentry conditions

The same 3-stage methodology was used in order to determine $\gamma_w$ for the above subsonic air test regime, which simulates the EXPERT reentry conditions at the trajectory point 1 (the Table 4). The appropriate heat flux envelope is shown in Fig. 5. First of all we see that surface catalysis plays an essential role in stagnation point heat transfer in this test regime. The second point appears as a fact that the boundary layer on SiC sample is almost frozen. So, the test regime under consideration is very convenient in terms of accuracy to determine $\gamma_w$. Indeed, the position of the experimental point on the heat flux map gives the value $\gamma_w = 4.3\cdot10^{-3}$.

The results of determination of $\gamma_w$ for SiC material in the three regimes for the Pre-X vehicle and in one regime for the EXPERT vehicle are summarized in Fig. 6 together with prior results[11]. The data obtained with the large tile-like model show the strong trend: when the pressure increases, $\gamma_w$ decreases. This trend is similar to the results obtained for SiC in prior subsonic air tests with the euromodel made of sintered SiC[11]. The prior data gave higher values of $\gamma_w$ due to higher surface temperature (1770 K).

The present result for $\gamma_w$ obtained at the relatively high pressure 170 hPa at SiC surface temperature 1650 K is found to be quite close to the present result for SiC at $T_w$ = 1600 K obtained in the regime 3E (Table 3) using an euromodel as well. Probably the data of SiC catalycity at the pressure above 70 hPa indicate a weak dependency of $\gamma_w$ on pressure.

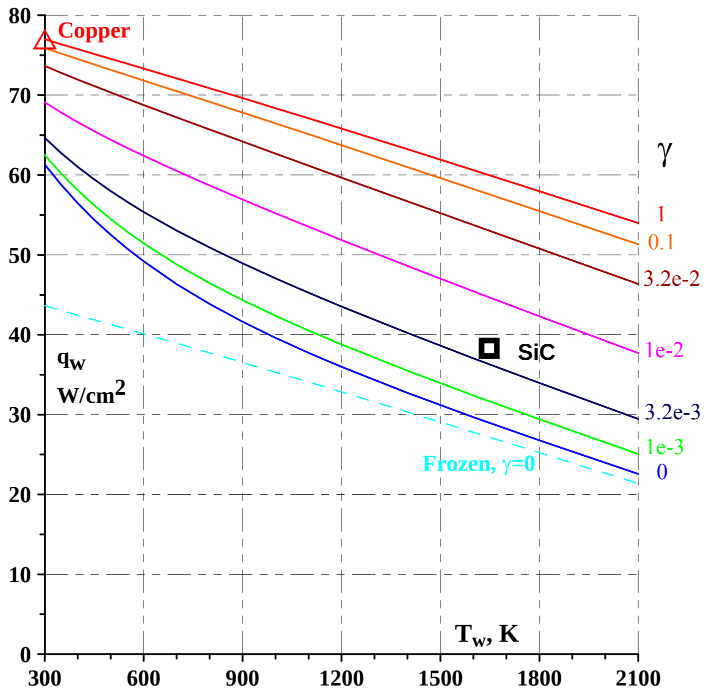


Figure 5: Heat flux envelope for the EXPERT test regime 1: $Z_m$=40 mm, $P_0$=170 hPa, $N_{pl}$=15 kW, $h_e$=7.7 MJ/kg, $V_0$=158 m/s. Measured SiC surface temperature and rebuilt heat flux are shown by the symbol

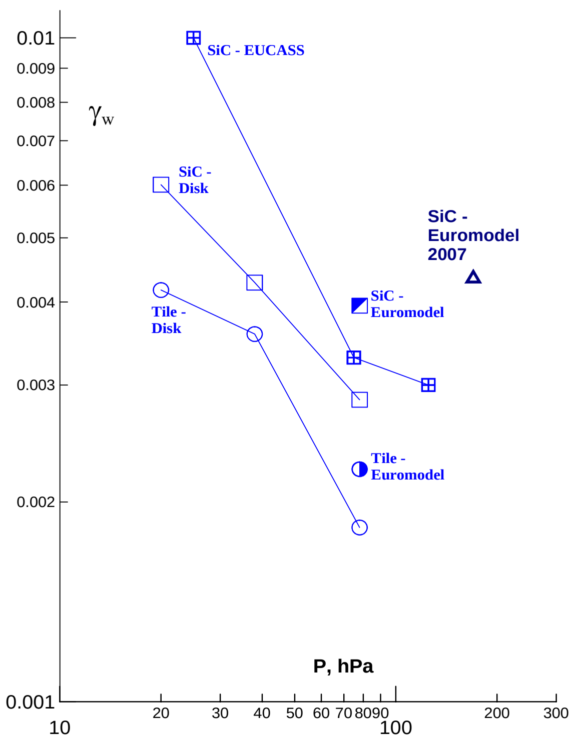


Figure 6: $\gamma_w$ determined for SiC in different regimes using different TPM models. Tile-like model: SiC (squares, $T_w$ = 1500 – 1600 K); borocilicate coating (circles, $T_w$ = 1470 – 1530 K). Euromodel Dm=50mm: separate symbols, SiC (half-filled square, $T_w$ = 1600 K; triangle, $T_w$ = 1650 K); tile (half-filled circle, $T_w$ = 1550 K). Prior data for SiC[11] (crossed square, $T_w$ = 1770 K)

## 6. Conclusions

The extended capabilities of the IPG-4 plasmatron based on the LHTS concept and being supported by flow characterization and CFD modeling are sufficient for the simulation of the stagnation point heat transfer for the Pre-X vehicle in subsonic high-enthalpy airflows using the new large-scale model (size 150 mm). This duplication predicts the reduction of the SiC surface temperature on 300-350 K with respect to fully catalytic wall at the peak heating part of the Pre-X trajectory. Complete duplication of the stagnation point heating in subsonic airflow using the IPG-4 plasmatron can be achieved for the reentry trajectory point at $V_\infty$ = 6120 m/s and Z = 65.4 km.

The IPG-4 plasmatron has sufficient capabilities to simulate the stagnation point heating for the EXPERT vehicle at relatively low reentry velocity and high stagnation pressure, if an euromodel with TPM sample and sonic nozzle with throat diameter 40 mm are used.

The catalytic recombination coefficient $\gamma_w$ for sintered SiC material is determined in the pressure range 20 – 78 hPa at the surface temperature 1500 – 1600 K with respect to the Pre-X reentry trajectory and at the pressure 170 hPa and surface temperature 1650 K with respect to the EXPERT reentry trajectory. When the pressure increases in the range 20 – 80 hPa, $\gamma_w$ decreases in the range $6\cdot10^{-3}$ - $3\cdot10^{-3}$. The data of $\gamma_w$ obtained for SiC in the two regimes at the pressures 78 ($T_w$ = 1600 K) and 170 hPa ($T_w$ = 1650 K) are found to be quite close. Probably this result indicates that pressure does not much affect the recombination coefficient in this pressure range.

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