PREDICTING CATALYCITY OF SI-BASED COATING AND STAGNATION POINT HEAT TRANSFER IN HIGH-ENTHALPY CO_2 SUBSONIC FLOWS FOR THE MARS ENTRY CONDITIONS

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ABSTRACT

An average catalytic efficiency ã*w* of the Si-based material with respect to surface recombination reactions $O+O+SO_2+S$ and $CO+O+SCO_2+S$ is rebuilt through CFD modeling the stagnation point heat transfer for subsonic high-enthalpy carbon dioxide tests conducted by 100-kW inductively heated facility. Dependence of ã*w* versus pressure is found in the pressure range 60-140 hPa at surface temperature 1600-1630 K. The extrapolation of the test data to the Martian atmosphere entry conditions based on the concept of the local heat transfer simulation predicts the reduction of the stagnation point heat flux by a factor of 1.8 and surface temperature on 250 K for the Si-based material against fully catalytic heating.

1. INTRODUCTION

The predicting surface catalycity of the thermal protection material (TPM) in dissociated carbon dioxide gas - the dominant chemical component (~96 %) in the Martian atmosphere - is rather important for selection of TPM for the Mars missions in terms of reduction of surface heating and diminution in a mass of the thermal protection system [1-4]. The methodology for predicting TPM catalycity in subsonic dissociated CO_2 flows combined with the direct duplication of the stagnation point heat transfer for the Mars probe entry conditions by the 100-kW IPG-4 plasmatron [5] has been developed in [6-9]. The average catalytic efficiency ã*w* of the Si-based coating with respect to O atoms and CO molecules recombination was determined in the pressure range 74-100 hPa and surface temperature range 1470-1670 K in [6-9].

This paper is devoted to predicting catalytic efficiency ã*w* of the Si-based coating in subsonic high-enthalpy carbon dioxide flow at the high surface temperature in the pressure range 60-140 hPa, which includes the stagnation pressure at the peak-heating trajectory points of the "Mars Pathfinder" [3], "Mars Probe" [10] and Mars Decent Vehicle [11]. To study how the pressure affects TPM catalycity is necessary for the further development of the phenomenological models of the surface catalysis for the Mars entry conditions as well.

The heat transfer tests in subsonic highly dissociated carbon dioxide gas flows were conducted in the pressure range 60-140 hPa at the enthalpy 16.7-17 MJ/kg by the IPG-4 plasmatron. The characterization of the free stream conditions included measurements of the dynamic pressure and stagnation point heat flux to high catalytic cold wall (silver). The characterization of stagnation point heat transfer included measurements of the surface temperature of the Si-based sample by pyrometry and heat losses inside the sample by waterflow calorimeter.

CFD modeling for the catalycity test conditions included computations of the equilibrium inductively coupled CO_2 plasma flow, flow field past a 50-mm diameter euromodel and nonequilibrium boundary layer with a finite thickness for 5-species dissociated carbon dioxide mixture. Numerical analysis of the IPG-4 subsonic carbon dioxide test data within above pressure range has revealed that the catalytic efficiency of the Sibased material increases, when the pressure decreases at high surface temperature 1600-1630 K.

Extrapolation of the ground high-enthalpy test

conditions and data of surface catalycity to the Marts entry conditions has been performed on the basis of the concept of local heat transfer simulation (LHTS) [12-15]. In order to do that, the results of the characterization of the free stream conditions and CFD modeling of flow field in the plasma torch and around a model were used. For the three subsonic test conditions at different pressures, the three appropriate sets of the entry parameters (velocity, altitude and nose radius) were calculated.

2. IPG-4 FACILITY

The multipurpose plasmatron IPG-4 is the inductively heated 100-kW power R&D facility with the 80-mm diameter channel [5-9]. The IPG-4 operating envelope in subsonic high-enthalpy regime with carbon dioxide gas covers the peak-heating parts of the "Mars Pathfinder" [3], "Mars Probe" [10] and MDV [11] trajectories (Fig. 1). In the IPG-4 facility the pressure and free stream enthalpy can be controlled smoothly and independently. This feature combined with a high reproducibility of chemically pure plasma parameters provides the unique capability to rebuild the TPM catalycity on the basis of the heat transfer measurements and modeling [6-9].

Fig. 1. Operating envelope of the IPG-4 plasmatron in subsonic regime with carbon dioxide plasma in coordinates "stagnation pressure-total enthalpy" and the Mars entry trajectories of the "Mars Pathfinder" [3], "Mars Probe" [10] and Mars Decent Vehicle [11]. Stars indicate the peak-heating points.

The mass flow rate 1.8 g/s through discharge channel was found to be the optimum one for the subsonic tests with carbon dioxide gas. At the optimum mass flow rate, the stable inductively coupled plasma exists in the whole operating envelope for a long run time. This feature provides the possibility to study heat transfer in the steady-state regimes. The important advantage of the IPG-4 plasmatron over existing arc-jet facilities appears due to quite small mass flow rate of CO in plasmatron jet core.

The IPG-4 facility can operate in supersonic regime as well, but for the case under consideration, when $R_m << R_N$, where R_m is model radius and R_N is blunt nose radius, only subsonic test can provide adequate duplication of the stagnation point heat transfer [12-15].

3. TEST INSTRUMENTATION and MEASUREMENT TECHNIQUES

The methodology of the aerothermal testing in inductively coupled plasma flows and measurement techniques have been developed in [5-9] for researches of the heat transfer, testing TPM samples, study of plasma/surface interaction and real gas effects. The characterization of the subsonic plasma flows and heat transfer includes the measurements of the steady-state free stream and heat transfer parameters as follows:

1) dynamic pressure;
2) stagnation point heat fluxes to silver cooled surface (standard high-catalytic material in dissociated carbon dioxide mixture [9]);
3) TPM surface temperature;
4) heat losses into TPM sample.

The dynamic pressure p_{dyn} was measured by watercooled Pitot probe as the difference between stagnation pressure and static pressure at the test chamber wall. The pressure transducers with the upper limits 125 hPa (the accuracy ±0.4 hPa) and 16 hPa (the accuracy ±0.02 hPa) are included in the list of instrumentation. For the stagnation point heat transfer measurements the water-cooled model manufactured of copper and the sample holder assembled with the SiC-mask, both of the

standard euromodel geometry, were used. The water flow steady-state calorimeters made of copper with the heat-adsorbing face covered with silver were used in the cooled wall tests. The 14-mm diameter heat-adsorbing calorimeter surfaces were polished to a mirror quality. In order to improve the measurement reproducibility, the probe surface should be thermochemically cleaned in the plasma flow in the course of a few minutes. Previously, in subsonic tests with dissociated carbon dioxide the silver surface was found as the best catalyst among cooled metals [7-9], whereas in dissociated air and dissociated nitrogen tests copper showed the highest catalytic activity [13].

In the cooled wall tests, the stagnation point heat flux is determined through the measured water flow rate through the probe and water temperature difference between the probe outlet and inlet sections. The accuracy of measurement of the stagnation point heat flux for a cooled surface (T_w ¡Ö300 K) is ±5 %.

The model with the TPM sample, prepared from Sibased material, was located at the 60-mm distance from the plasmatron exit section in stagnation point configuration. Two heat transfer parameters were measured after transition to the steady-state heat transfer regime: the surface temperature (by pyrometry) and heat loss from the rear surface of the sample (by calorimetry).

The brightness temperature of the glassy black coating was measured by two photoelectric pyrometers, one of which operated in the temperature range 600-1300°C (ë=0.8-1.8 µk) and the other one in the range 1000-2000°C (ë=0.7-1.1 µk). The operating temperature range was chosen taking into account the spectral emissivity å$_e$ of the glassy coating as a function of the surface temperature and spectrum of the CO_2 plasma radiation. In the present measurements an average error of the temperature measurements was ±20 K. The intrinsic surface temperature T_w has been determined taking into account the sample spectral emissivity and spectral transparency of the optical quartz window in the testing chamber.

The stagnation point heat flux was rebuilt by the formula

c q w T th w q + ó å = 4 (1)

In Eq. 1 å$_{th}$ is the total hemispheric emissivity of the surface, ó is the Stefan-Boltzmann constant, q_c is the heat loss from the rear sample surface. The data of [16] were used for the optical properties of the Si-based tile coating at high surface temperature (å$_{th}$=0.89-0.82 in the temperature range 1200-1700 K).

4. CFD TOOLS

The numerical modeling subsonic plasma flows and high-enthalpy reacting gas flows and heat transfer for the plasmatron test conditions is an integral part of the free stream characterization, predicting surface catalycity and extrapolation from ground to atmospheric entry flight [6-9,13-15]. For the considered plasmatron operating conditions (p¡Ý60 hPa) in subsonic regime, the main CFD problem for the modeling high-enthalpy carbon dioxide plasma and reacting gas flows is divided in three parts as follows:

1) equilibrium inductively coupled axisymmetric swirling CO_2 plasma flow within cylindrical discharge channel;

2) equilibrium subsonic axisymmetric high-enthalpy laminar jet flow of dissociated CO_2 mixture around a cylindrical model;

3) nonequilibrium multicomponent boundary layer of dissociated CO_2 mixture at the stagnation point.

The first problem is treated with taking into account the

plasmadynamics effects of the Lorentz force and Joule heat release in the plasma torch. The 2D Navier-Stokes equations written for the total enthalpy and three velocity components including the tangential component due to the flow swirling coupled with the simplified quasi 1D Maxwell equation for the averaged complex amplitude of the electric field tangential component generating vortical electric currents are used for the computations of reacting plasma flows within the discharge channel [9,17].

For CFD modeling the finite difference analogies of the Navier-Stokes equations written for the control volumes of the staggered grid were used. The governing equations were solved by a method analogous to the SIMPLE method [18]. The final system of the linear algebraic equations was solved by the modified method of incomplete factorization. The simplified equation for the complex amplitude of the electric field averaged in time was solved by an effective technique based on the Thomas algorithm.

-40
0
40
0.001
0.01
0
0
-0.01
-0.03
0.6
0.1
0.001
0.01
0.3
r a)
b)
0 100 200 300 400 -40
0
40
1000
2000
3000
6000
7000
7500
6000
5000
4000
3000
2000
r
Z,mm

Fig. 2. Isolines of the stream function (a) and isotherms, K, (b) in the IPG-4 discharge channel for the CO_2 equilibrium plasma flow.

Fig. 2 shows isolines of the stream function and isotherms in the IPG-4 discharge channel for the CO_2 equilibrium plasma flow at the pressure p=140 hPa, the mass flow rate G=1.8 g/s, the power input in plasma N_{pl}=14.8 kW, the electric current frequency f= 1.76 MHz.

The full 2D Navier-Stokes equations for the enthalpy, two velocity components and pressure were used for modeling the laminar subsonic equilibrium highenthalpy carbon dioxide flows over a model (ionization and flow swirling were not essential in this problem). The grounds for the equilibrium approach stand on the specific features of subsonic high-enthalpy flows in plasmatron at pressure above 50 hPa. The approach consists in the use of computations for the subsonic equilibrium flow field around a model serving only as the external solution for the nonequilibrium boundary layer problem. Fig. 3 shows streamlines and isotherms in the subsonic high-enthalpy CO_2 jet flow over the euromodel in the IPG-4 plasmatron at the same regime as in Fig. 2.

The one-dimensional approach for the nonequilibrium boundary layer with the finite thickness is used in order to calculate stagnation point heat transfer rates for the subsonic test conditions [6-9,13,14]. This concept makes it possible to efficiently separate the accurate computations of the stagnation point heat transfer rates and the solution of the full Navier-Stokes equations for the bulk flow. The 1D mathematical model of the boundary layer for the reacting gas takes into account the finite thickness of the boundary layer and flow vorticity at the outer edge of the boundary layer by

means of the three dimensionless parameters which have to be obtained from the solution of the full Navier-Stokes equations in advance. The 1D code can run autonomously in the wide domain of the test conditions, surface temperature and catalytic efficiency. The finite difference scheme of the four-order approximation was used for the fast and accurate numerical solution of the 1D boundary layer problem.

0 50 100 150 -60
-40
-20
0
20
40
60
0.01
0.1
0.3
0.7
1
1.2
1.1
Z, mm
r
a)
0 50 100 150 -60
-40
-20
0
20
40
60
3000
4000
5000
6000
2000
1000
350
500
Z, mm
r
b)

Fig. 3. Streamlines (a) and isotherms, K, (b) in the CO_2 subsonic equilibrium jet flow over the euromodel in the IPG-4 plasmatron at p=140 hPa, G=1.8 g/s, N_{pl}= 14.8 kW, f=1.76 MHz.

Computations were performed for the nonequilibrium 5-species (CO_2, CO, O_2, C, O) boundary layer. The assumptions were assumed in the thermochemical model as follows:

1) molecules vibrations are in equilibrium excitation, chemical kinetics is one-temperature; the data on rate constants for gas-phase reactions were been taken from [19];

2) a: surface catalytic reactions $O+OO_2$ and $CO+OCO_2$ are the first order reactions with the same recombination coefficient $\tilde{a}_w$, or

b: surface is non-catalytic to CO molecules recombination ($\tilde{a}_{wCO}$=0).

5. REBUILDING FREE STREAM CONDITIONS

The three measured parameters - stagnation point heat flux to cooled silver surface, static pressure and dynamic pressure - are indispensable and sufficient ones for the rebuilding free stream conditions, if the flow core is under thermochemical equilibrium. The measured heat flux to silver surface was related to fully catalytic wall. The all free stream parameters at the subsonic jet axis (velocity, enthalpy, temperature and chemical composition) were rebuilt through multiparameter computations of the stagnation point heat transfer to fully catalytic wall with the assumption that the chemical composition of the 5-species dissociated carbon dioxide mixture is under equilibrium at the edge of the boundary layer.

6. DETERMINATION OF THE SI-BASED SURFACE CATALYCITY

The computed heat transfer rates for the three specified test conditions are presented as the heat flux charts in Figs. 4-6. The solid curves *1-7* correspond to constant values $\tilde{a}_w$ in the range 1-0. The curves *8* relate to the frozen boundary layer and $\tilde{a}_w$=0. The all three charts are

matched at the upper left corners with the measured heat fluxes to the cooled silver surface assumed to be fully catalytic.

Fig. 4. Heat flux chart for $C0_2$ test conditions: p=60 hPa, p_{dyn}=22.5 Pa, h_e=16.7 MJ/kg, V_S=122m/s, T_e=3940 K; ã$_w$=1.0; 0.1; 0.032; 0.01; 0.0032; 0.001; 0; 0 (frozen).

Fig. 5. Heat flux chart for $C0_2$ test conditions: p= 100 hPa, p_{dyn}=14 Pa, h_e=17 MJ/kg, V_S=76 m/s, T_e= 4140 K; ã$_w$=1.0; 0.1; 0.032; 0.01; 0.0032; 0.001; 0; 0 (frozen).

Fig. 6. Heat flux chart for $C0_2$ test conditions: p= 140 hPa, p_{dyn}=10 Pa, h_e=16.7 MJ/kg, V_S=54 m/s, T_e= 4020 K; ã$_w$=1.0; 0.1; 0.032; 0.01; 0.0032; 0.001; 0; 0 (frozen).

The locations of the experimental points for the Sibased TPM inside the heat flux charts are determined by the two measured coordinates: q_w and T_w. Accordingly to the algorithm developed in [13,6-9], the surface catalycity is determined by the position of the experimental data with respect to the curves ã$_w$=*const*. One set of the subsonic high-enthalpy test conditions gives single experimental point and single ã$_w$ value at the appropriate measured surface temperature.

From Figs. 4-6 we have extracted ã$_w$ for the Si-based surface in the pressure range 60-140 hPa at the surface temperature 1600-1630 K. The data of effective recombination coefficient ã$_w$ are given in Fig. 7. The clear trend in the behavior of ã$_w$ versus pressure is observed as follows: ã$_w$ increases from $3.2\cdot10^{-3}$ to $9.4\cdot10^{-3}$, when the pressure decreases in the range 140-60 hPa at T_w=1600-1630 K.

The distance between curves 7 and 8 in Figs. 4-6 presents the contribution of the nonequilibrium gas phase reactions in boundary layer in the stagnation point heat transfer rates for non-catalytic wall. It is clear that the boundary layer at the non-catalytic wall can not be considered as a frozen one in the all three high-enthalpy aerothermal tests considered here.

0.004 0.008 0.012 0.016 0.02
0.001
0.01
1 / p
ã
w

Fig. 7. Effective recombination coefficient for Si-based coating in dissociated CO_2 mixture versus $1/p$, $(hPa)^{-1}$, at T_w=1600-1630 K.

The second model of the wall catalysis considered in the present investigation was one based on the assumption that Si-based coating is non-catalytic to carbon monoxide recombination: ã$_{wCO}$=0. That assumption has come from the experimental investigation of surface reactions on quartz in carbon monoxide and oxygen mixtures in a dead-end, diffusion tube side-arm reactor at low pressure 41.5-50.7 Pa and low quartz surface temperature 292-623 K [20].

In all three cases of different tests conditions considered in the present paper, the assumption ã$_{wCO}$=0 has led to conclusion that Si-based surface is fully catalytic with respect to recombination of atomic oxygen (ã$_{wO}$=1), unlike our previous results [7] and all other available experimental data [21]. This result means, that at high temperature Si-based surface can not be considered as a non-catalytic with respect to CO molecules recombination.

7. EXTRAPOLATION to THE MARS ENTRY CONDITIONS

Determination of the single effective recombination coefficient ã$_w$ for the two surface catalytic reactions $O+O+SO_2+S$ and $CO+O+SCO_2+S$ and further implementation of ã$_w$ in CFD codes developed for

computations of flow field and heat transfer for the Martian atmosphere entry conditions appears as an efficient and accurate way, if we support this procedure with a correct extrapolation from high-enthalpy ground testing to hypersonic free flight [12-15].

The LHTS concept of such extrapolation for stagnation point configuration is based on the requirements to duplicate in high-enthalpy tests the same total enthalpy, stagnation pressure and velocity gradient at the outer edge of the boundary layer of the model as in hypersonic flight [13-16]. By means of this theory, the ground test data can be extrapolated to flight conditions as follows:

s h V 2 (2)

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s p

1 2

(3)

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x

Se U

S V

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m R (5)

In Eqs. 2-5 subscripts and *S* denote the free stream conditions in hypersonic flight and subsonic highenthalpy flow, R_N is a nose radius and * *m R* is an effective radius of the test model at the stagnation point.

After recalculating the three subsonic tests conditions given in Table 1 to hypersonic free stream parameters using Eqs. 2-4, we have found the three sets of entry conditions presented in Table 2.

Table 1

IPG-4	h_e, MJ/kg	P, hPa	V_S, m/s	R_m, m
I	16.7	60	122	0.025
II	17	100	76	0.025
III	16.7	140	54	0.025

Table 2

ENTRY	H, MJ/kg	Z, km	V, m/s	R_N, m
I	16.7	46	5780	0.65
II	17	42	5830	1.04
III	16.7	39	5780	1.48

For all these entry conditions in the Martian atmosphere according to Figs. 4-6 we numerically have predicted the same stagnation heat flux q_w= 60-62 W/cm^2 for fully

catalytic radiative equilibrium wall. An application of the Si-based coating for a heat protection shield should provide the reduction of the stagnation heat flux in a factor of 1.8 in comparison with fully catalytic heating. In the case of Si-based coating, the expected reduction of the TPM surface temperature is about 250 K against fully catalytic wall case.

8. CONCLUSIONS

In the present paper the catalytic efficiency γ_w of the Sibased coating with respect to recombination of atomic oxygen and carbon monoxide was determined and extrapolated to the entry conditions in the Martian atmosphere through performing three basic steps as follows: aerothermal testing TPM in subsonic highenthalpy carbon dioxide gas using the IPG-4 plasmatron - CFD modeling of flow field and stagnation point heat transfer for plasmatron test conditions - recalculation of the plasmatron subsonic free stream parameters and radius of the model to the entry velocity, altitude and vehicle nose radius on the basis of the LHTS concept.

Clear trend in the behaviour of γ_w is revealed: when the pressure increases in the range 60-140 hPa, γ_w decreases in the range 0.009-0.003 at surface temperature 1600-1630 K. The Si-based coating can not be considered as a noncatalytic with respect to CO molecules recombination.

The data of γ_w are obtained at subsonic high-enthalpy carbon dioxide test conditions, which simulate boundary layer conditions at the stagnation point in the Martian atmosphere for the entry velocity about 5800 m/s, the altitude range 46-39 km and nose radius of a vehicle in the range 0.65-1.5 m. The data of the stagnation point heat transfer presented here can be considered as the direct duplication of the heat flux for the three different sets of the free hypersonic flight conditions. Therefore, we can predict that at these entry conditions an application of the Si-based TPM should provide the reduction of the surface temperature on 250 K in comparison with a fully catalytic radiative equilibrium wall.

In the all test regimes considered here, the gas-phase reactions affect the stagnation point heat transfer. Therefore, the accuracy of the rate constants for the gasphase reactions appears as an important factor in predicting TPM surface catalycity. Furthermore, the same rate constants of gas-phase reactions should be used in CFD codes devoted to determination of γ_w and predicting atmospheric entry heating.

9. ACKNOWLEDGEMENTS

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