SIMULATION OF HEAT TRANSFER AND SURFACE CATALYSIS FOR EXOMARS ENTRY CONDITIONS

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MOTIVATION

• At Mars entry conditions surface recombination of O and CO introduces a large portion of uncertainty in laminar convective heating

• Surface catalysis in terms of $O + O \rightarrow O_2$ and $CO + O \rightarrow CO_2$ reactions is one of the key issues of TPM development

• Requirements of reproduction of EXOMARS entry environment by RF-plasmatron and rebuilding recombination coefficients for O and CO on metals and quartz
OBJECTIVES

• Simulation of stagnation point heat transfer to cooled surfaces for EXOMARS entry in terms of total enthalpy and stagnation pressure in subsonic 97%CO₂+3%N₂ plasma flows

• Prediction of recombination coefficients $\text{O}_2$ and $\text{CO}_2$ on silver, copper, stainless steel and quartz at specified enthalpy and stagnation pressure of subsonic CO₂ plasma flows
Laminar convective heat flux along the Mars Pathfinder base line at peak heating point
100-kW RF-PLASMOTRON IPG-4
## MAIN PARAMETERS OF IPG-4 FACILITY

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency, MHz</td>
<td>1.76</td>
</tr>
<tr>
<td>Torch diameter, mm</td>
<td>80</td>
</tr>
<tr>
<td>Anode power, kW</td>
<td>12-76</td>
</tr>
<tr>
<td>Pressure, hPa</td>
<td>6-1000</td>
</tr>
<tr>
<td>Mass flow rate, g/s</td>
<td>1.8-6.0</td>
</tr>
<tr>
<td>Working gases</td>
<td>Air, N2, O2, CO2, Ar</td>
</tr>
</tbody>
</table>
RF-discharge in air and carbon dioxide flows

Air plasma at $P=100$ hPa, $G=2.4\text{ g/s}$, $N=45\text{ kW}$

Carbon dioxide plasma at $P=100$ hPa, $G=1.8\text{ g/s}$, $N=45\text{ kW}$
TPM testing in subsonic air and carbon dioxide plasma flows

Thermal protection tile surface with catalytic ring in air plasma flow

Thermal protection tile in carbon dioxide flow
Water-cooled test model with heat flux probe

1 – copper body
2 – water-flow calorimeter
## Test matrix

<table>
<thead>
<tr>
<th>Test facility</th>
<th>enthalpy [MJ/kg]</th>
<th>stagnation pressure [hPa]</th>
<th>model diameter [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPG-4</td>
<td>13.8</td>
<td>80</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>9.0</td>
<td>80</td>
<td>50</td>
</tr>
</tbody>
</table>
Heat flux probe with silver surface

Before testing

After testing in CO2 plasma flow
Heat flux measurements

Time history of heat flux to silver surface

Heating effect due to surface catalysis

Graphs showing heat flux measurements over time and the heating effect due to surface catalysis for different materials.
Rebuilding enthalpy of CO2 flows

Enthalpy vs anode power

Enthalpy along subsonic jet
Heat fluxes to different materials at specified test conditions

Heat flux vs anode power at p0 = 80 hPa, G=2.8 g/s
CFD modeling ICP flows (97%CO2 + 3%N2): isolines of stream function and isotherms

P=80 hPa, Np=20.28 kW, G=2.8 g/s
CFD modeling dissociated (97%CO2 + 3%N2) flow past a model

Stream lines
Isotherms

P=80 hPa, Npl=20.28 kW, G=2.8 g/s
Model of surface chemistry for boundary layer problem

- adsorption of the oxygen atoms dominants over other species adsorption;

- adsorption of O atoms and desorption of the products are fast reactions;

- recombination reactions follow Eley-Rideal mechanism:

  \[
  \begin{align*}
  O + S & \rightarrow O_{\_S}; \\
  O + O_{\_S} & \rightarrow O_2 + S; \\
  CO + O_{\_S} & \rightarrow CO_2 + S;
  \end{align*}
  \]

- recombination of C atoms on surface is negligible
Models of surface catalysis: boundary conditions for diffusion fluxes of O and CO at the wall

**Standard model**

\[-J_O = \rho K_{WO} c_O\]
\[-J_{CO} = \rho K_{WCO} c_{CO}\]
\[J_C = 0\]

**New model**

\[-J_O = \rho K_{WO} c_O + \frac{m_O}{m_{CO}} \rho K_{WCO} c_{CO}\]
\[-J_{CO} = \rho K_{WCO} c_{CO}\]
\[J_C = 0\]

\[J_O + \frac{2m_O}{m_{CO}} \rho K_{WCO} c_{CO} + \frac{m_O}{m_{CO}} J_{CO} + J_O = 0\]

\[K_{Wi} = \frac{2 \gamma_{wi}}{2 - \gamma_{wi}} \sqrt{\frac{R_A T_W}{2 \pi m_i}}\]
Heat flux envelopes for catalysis standard and new models

\[ P=80 \text{ hPa}, \ Nap=40.4 \text{ kW}, \ he=14 \text{ MJ/kg}, \ wO=1 \times 10^{-2} \]
Heat flux envelopes for catalysis standard and new models

P=80 hPa, Nap=40.4 kW, he=14 MJ/kg, wO =1e3
\[ q_w = q_{wO} = q_{wCO} \]

<table>
<thead>
<tr>
<th>( P, ) hPa</th>
<th>material</th>
<th>( \text{Tw}, ) K</th>
<th>( q, ) W/cm(^2)</th>
<th>( q_{wO} ) specified by literature data</th>
<th>( q_{wCO} ) determined by novel model</th>
<th>( q_w ) determined by standard model</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>quartz</td>
<td>755</td>
<td>70</td>
<td>( 2 \times 10^{-3} )</td>
<td>( 6.0 \times 10^{-3} )</td>
<td>( 7.84 \times 10^{-3} )</td>
</tr>
<tr>
<td></td>
<td>steel</td>
<td>300</td>
<td>93</td>
<td>( 2.6 \times 10^{-3} )</td>
<td>( 6.1 \times 10^{-3} )</td>
<td>( 8.48 \times 10^{-3} )</td>
</tr>
<tr>
<td>80</td>
<td>quartz</td>
<td>600</td>
<td>45</td>
<td>( 2 \times 10^{-3} )</td>
<td>( 3 \times 10^{-3} )</td>
<td>( 4.97 \times 10^{-3} )</td>
</tr>
<tr>
<td></td>
<td>steel</td>
<td>300</td>
<td>66</td>
<td>( 2.6 \times 10^{-3} )</td>
<td>( \text{n/a} )</td>
<td>( 1.07 \times 10^{-2} )</td>
</tr>
</tbody>
</table>
Extrapolation of heat transfer tests to re-entry conditions

- $H_2 = H_1$
- $P_{02} = P_{01}$
- $(U/s)_{e2} = (U/s)_{e1}$
- Flow field outside of boundary layer is under thermochemical equilibrium
Recalculation of subsonic test conditions to re-entry parameters (velocity, altitude, nose radius)
A. Kolesnikov, AIAA 2000-2515

\[ V_\infty = \sqrt{2h_s}, \quad \rho_\infty = \frac{p_s}{2(1 - k)h_s}, \quad R_N = \left( \frac{8}{3} k \right)^{1/2} \frac{\sqrt{2h_s}}{V_s} R_m^*, \quad k = \frac{\rho_\infty}{\rho_e} \]

<table>
<thead>
<tr>
<th>IPG-4</th>
<th>( h_e, \text{ MJ/kg} )</th>
<th>( p, \text{ hPa} )</th>
<th>( V_s, \text{ m/s} )</th>
<th>( R_m, \text{ m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>14.0</td>
<td>80</td>
<td>357</td>
<td>0.025</td>
</tr>
<tr>
<td>II</td>
<td>8.8</td>
<td>80</td>
<td>286</td>
<td>0.025</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mars entry</th>
<th>( V_\infty, \text{ m/s} )</th>
<th>( Z, \text{ km} )</th>
<th>( R_N, \text{ m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>5290</td>
<td>41.2</td>
<td>0.18</td>
</tr>
<tr>
<td>II</td>
<td>4200</td>
<td>38.1</td>
<td>0.16</td>
</tr>
</tbody>
</table>
CONCLUSIONS

• Simulation of stagnation point heat transfer for EXOMARS entry conditions carried out in subsonic test regimes at specified total enthalpy and stagnation pressure

• Recombination coefficients \( \text{O} \) and \( \text{CO} \) on quartz and stainless steel surfaces predicted in subsonic dissociated \( \text{CO}_2 \) flows using standard and new models for surface catalysis

• Adsorption of CO molecules should be included in catalysis model for copper surface
This work has been carried out in the framework of the SACOMAR Project (Technologies for Safe and Controlled Martian Entry)

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