SIMULATION OF HEAT TRANSFER AND SURFACE CATALYSIS FOR EXOMARS ENTRY CONDITIONS

A. Kolesnikov, A. Gordeev, S. Vasilevskii

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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

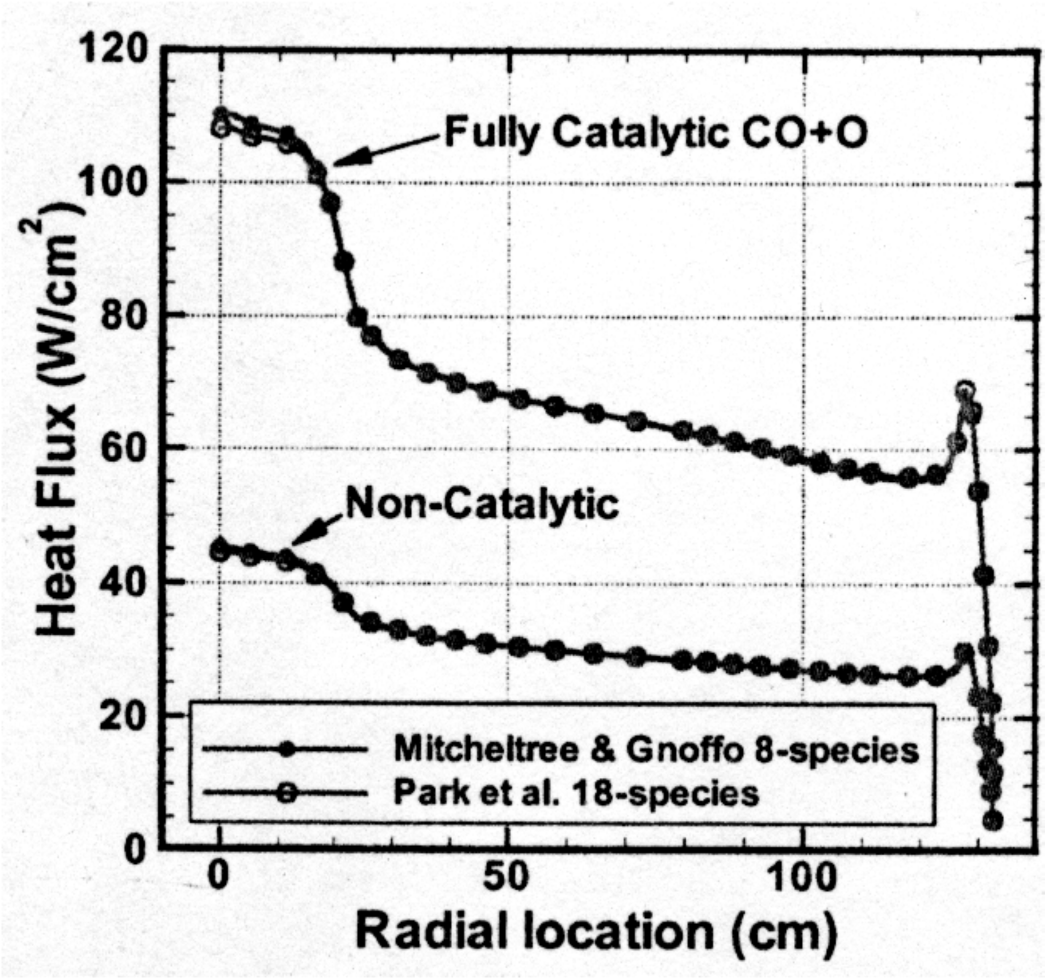
- Requirements of reproduction of EXOMARS entry environment by RF-plasmatron and rebuilding recombination coefficients γ_{O} and γ_{CO} on metals and quartz

OBJECTIVES

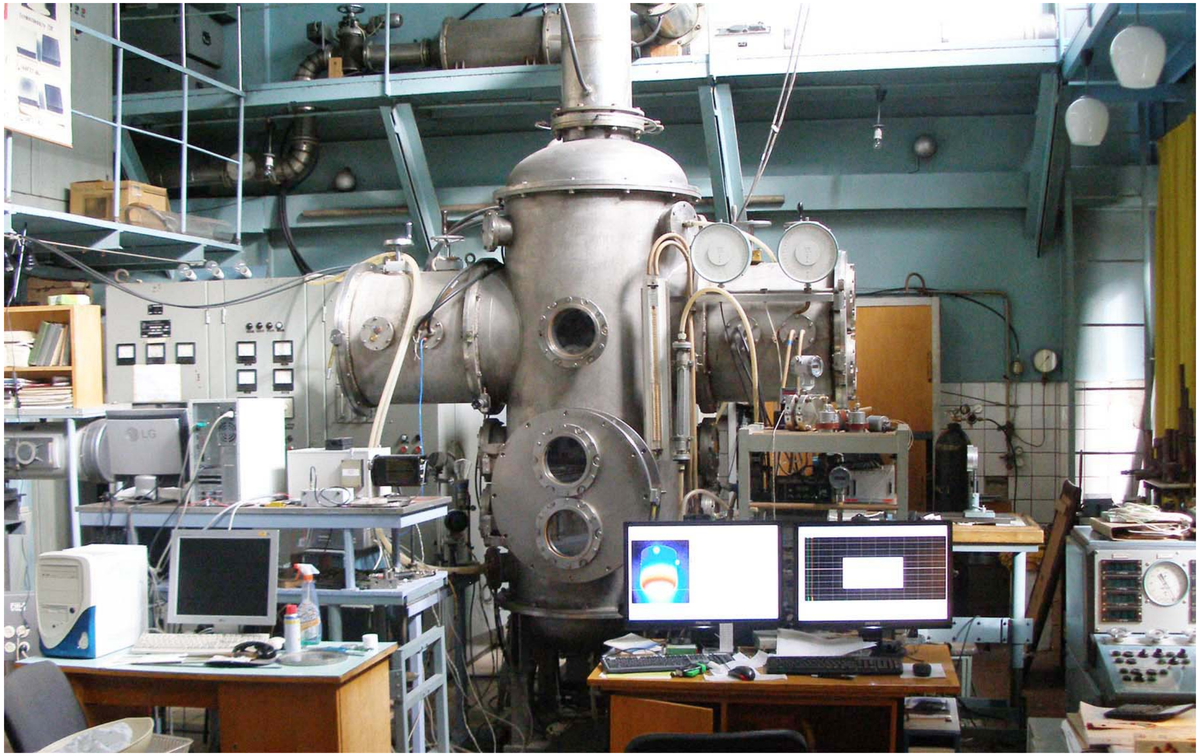
- Simulation of stagnation point heat transfer to cooled surfaces for EXOMARS entry in terms of total enthalpy and stagnation pressure in subsonic 97%CO_2+3%N_2 plasma flows

- Prediction of recombination coefficients γ_{o} and γ_{co} on silver, copper, stainless steel and quartz at specified enthalpy and stagnation pressure of subsonic CO_2 plasma flows

Laminar convective heat flux along the Mars Pathfinder base line at peak heating point



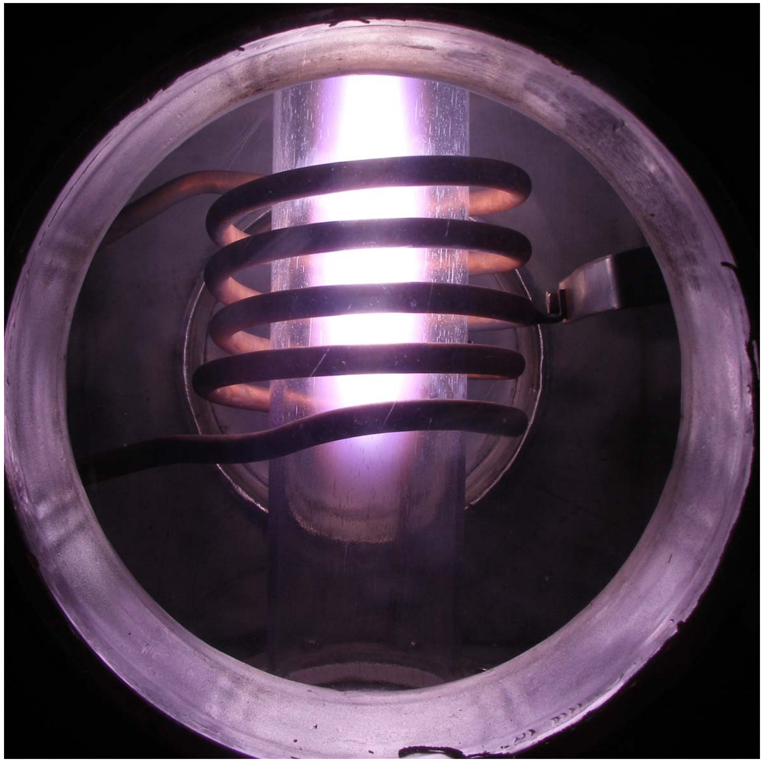
100-kW RF-PLASMOTRON IPG-4



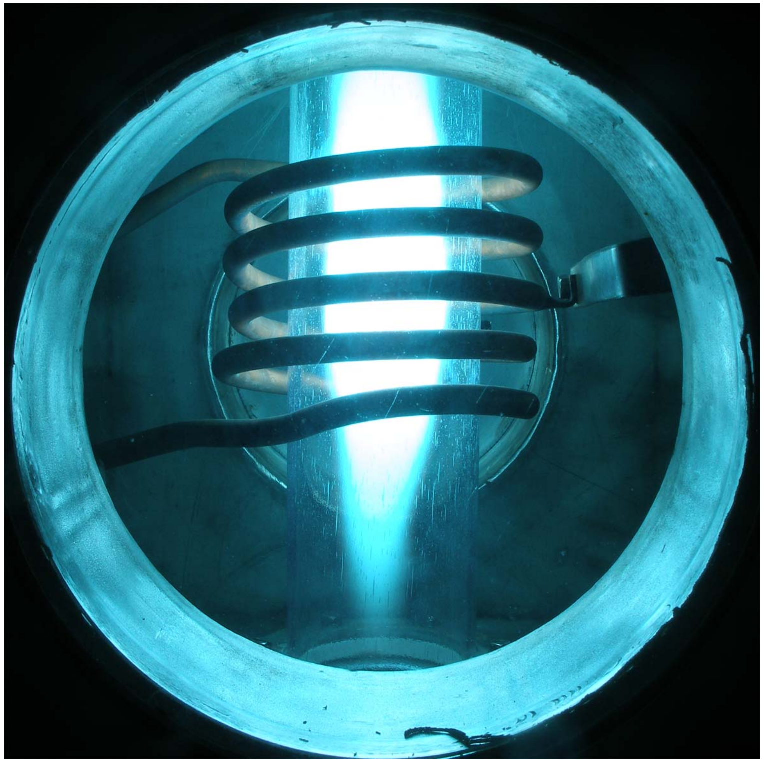
MAIN PARAMETERS OF IPG-4 FACILITY

Frequency, MHz	1.76
Torch diameter, mm	80
Anode power, kW	12-76
Pressure, hPa	6-1000
Mass flow rate, g/s	1.8-6.0
Working gases	Air, N_2, O_2, CO_2, Ar

RF-discharge in air and carbon dioxide flows



Air plasma at P=100 hPa,
G=2.4g/s, N=45 kW



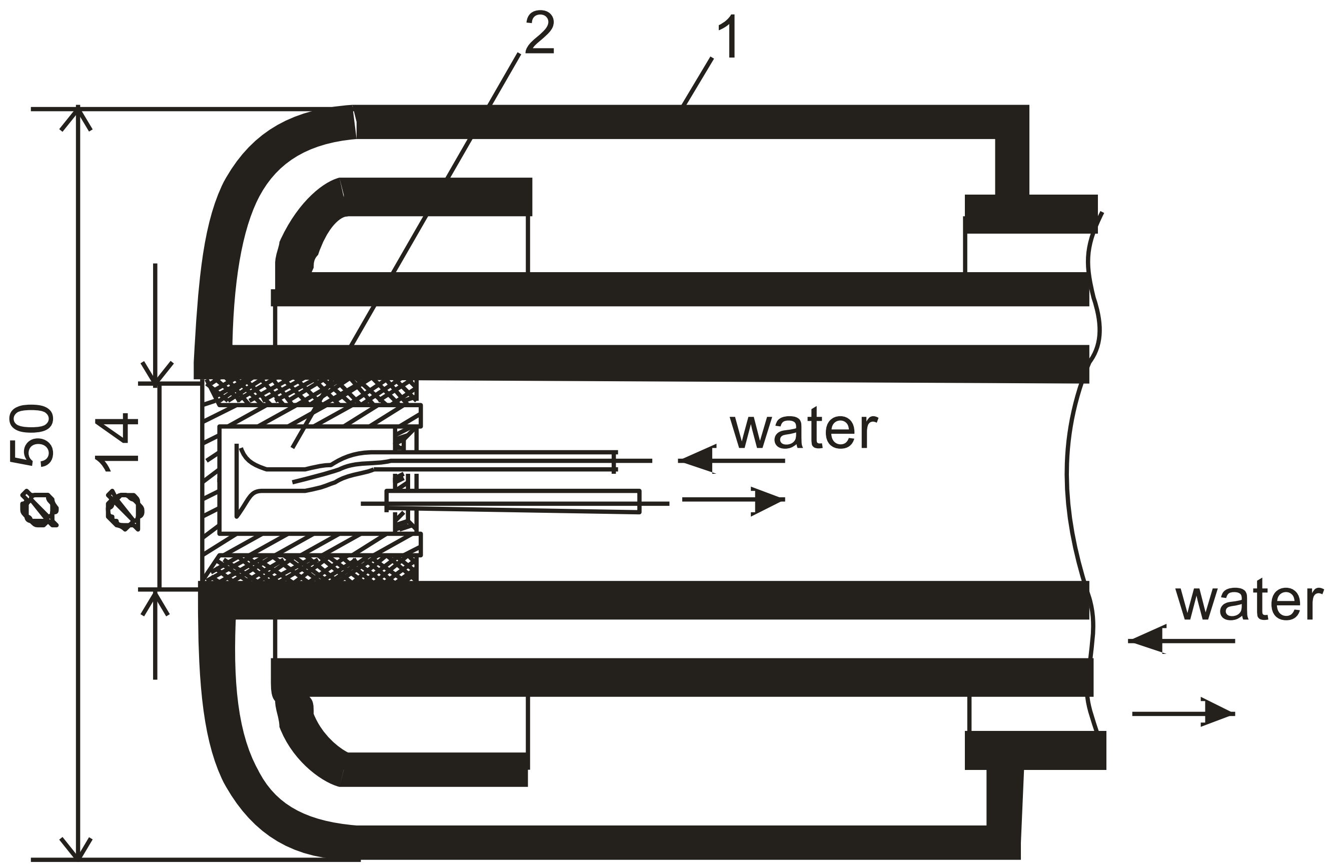
Carbon dioxide plasma at P=100 hPa,
G=1.8 g/s, N=45 kW

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

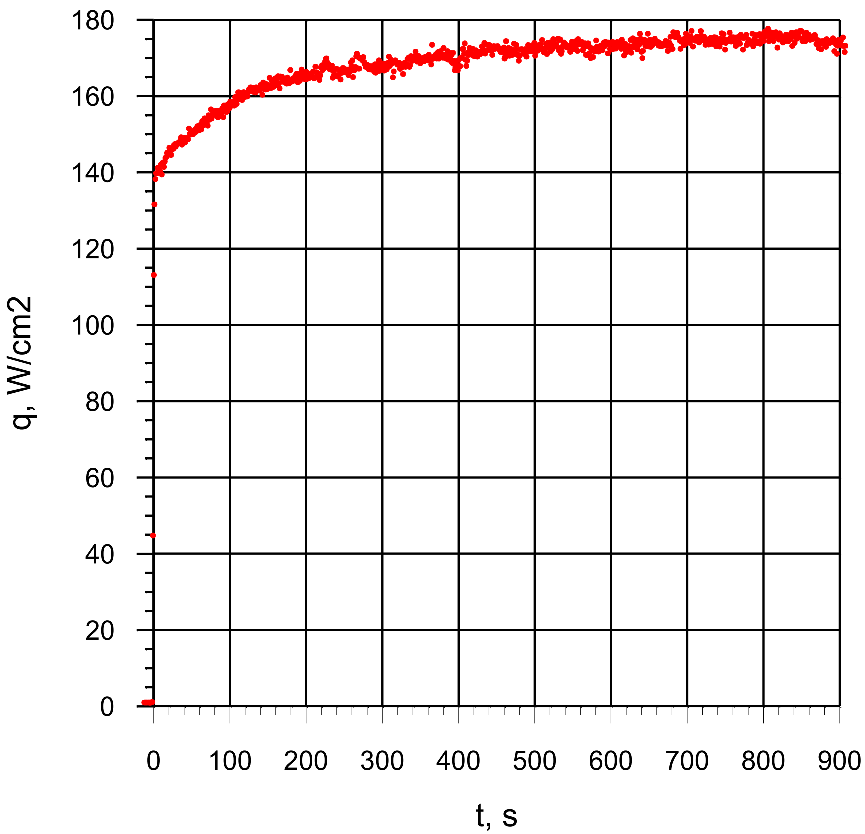
Test facility	enthalpy	stagnation pressure	model diameter
	[MJ/kg]	[hPa]	[mm]
IPG-4	13.8	80	50
	9.0	80	50

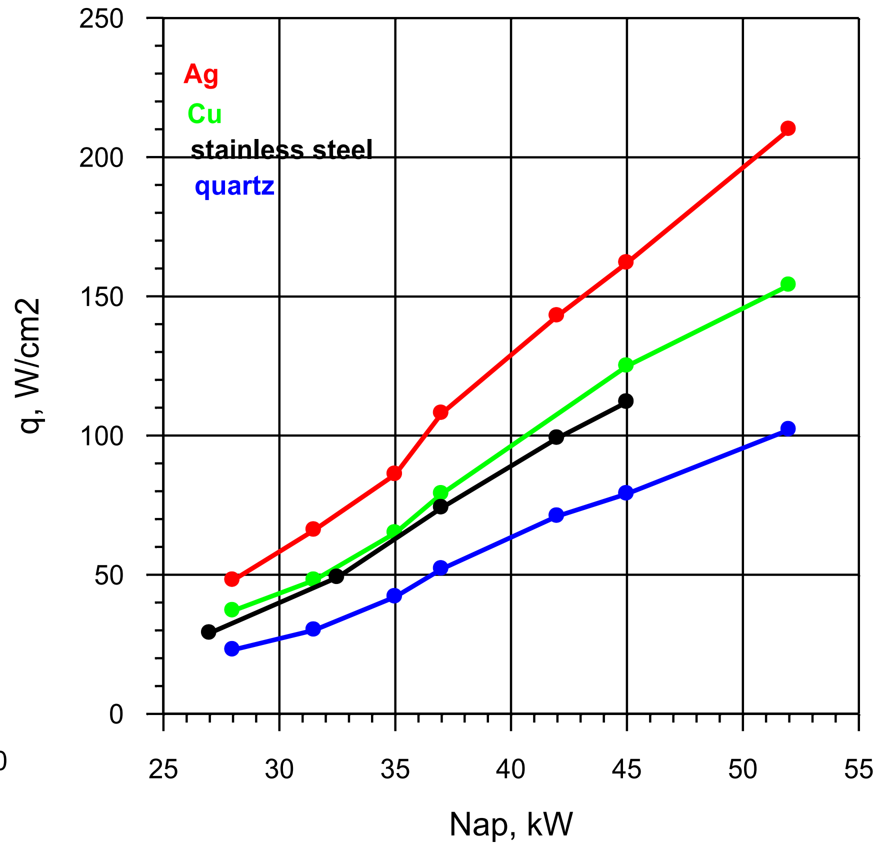
Heat flux probe with silver surface

Before testing

After testing
in CO_2 plasma flow

Heat flux measurements



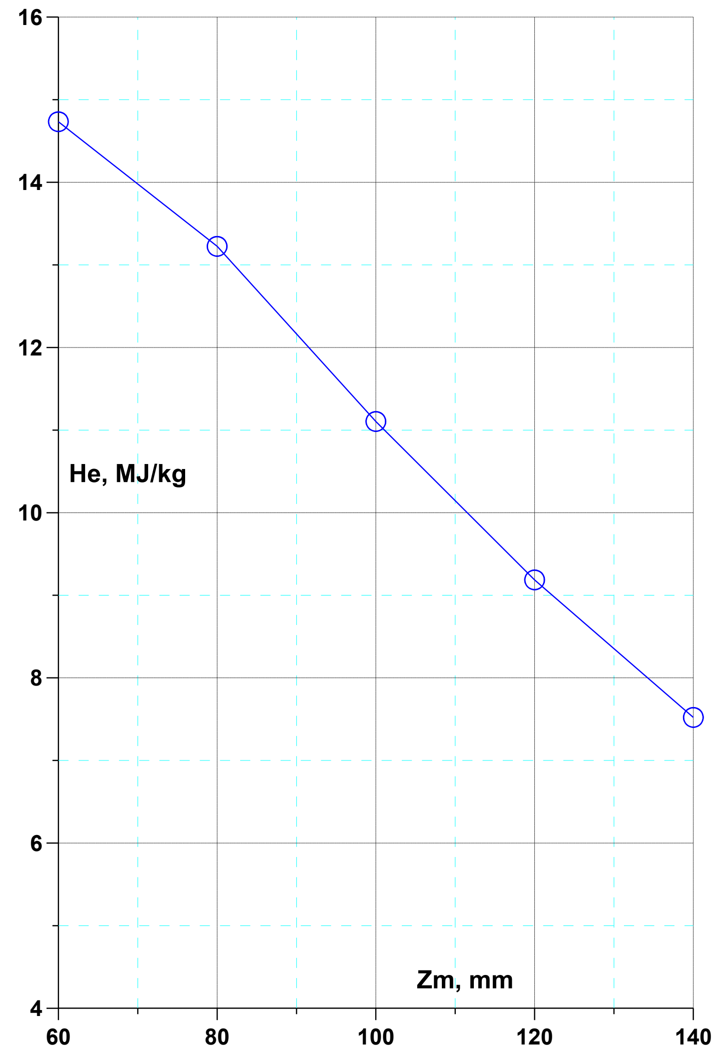


Time history of heat flux to silver surface

Heating effect due to surface catalysis

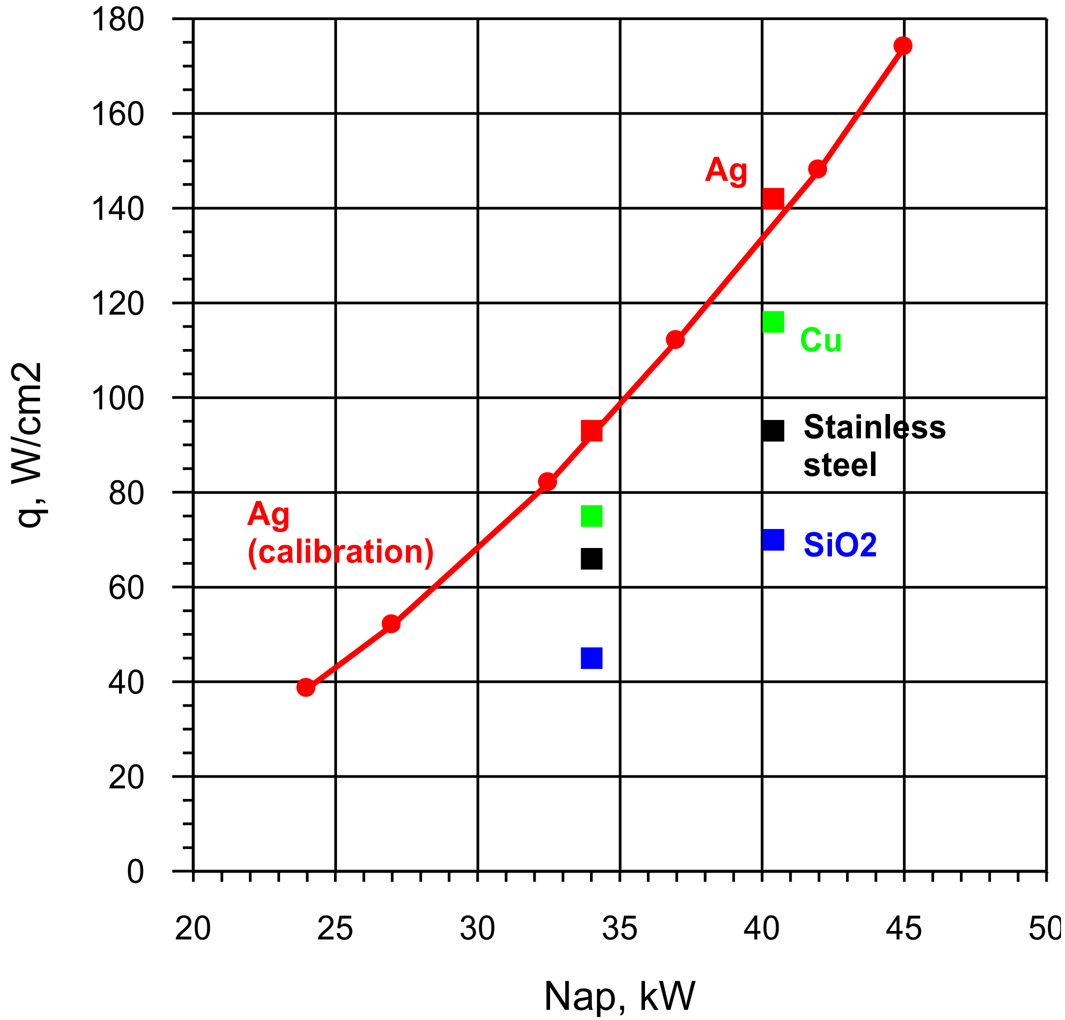
Rebuilding enthalpy of CO_2 flows

Enthalpy vs anode power



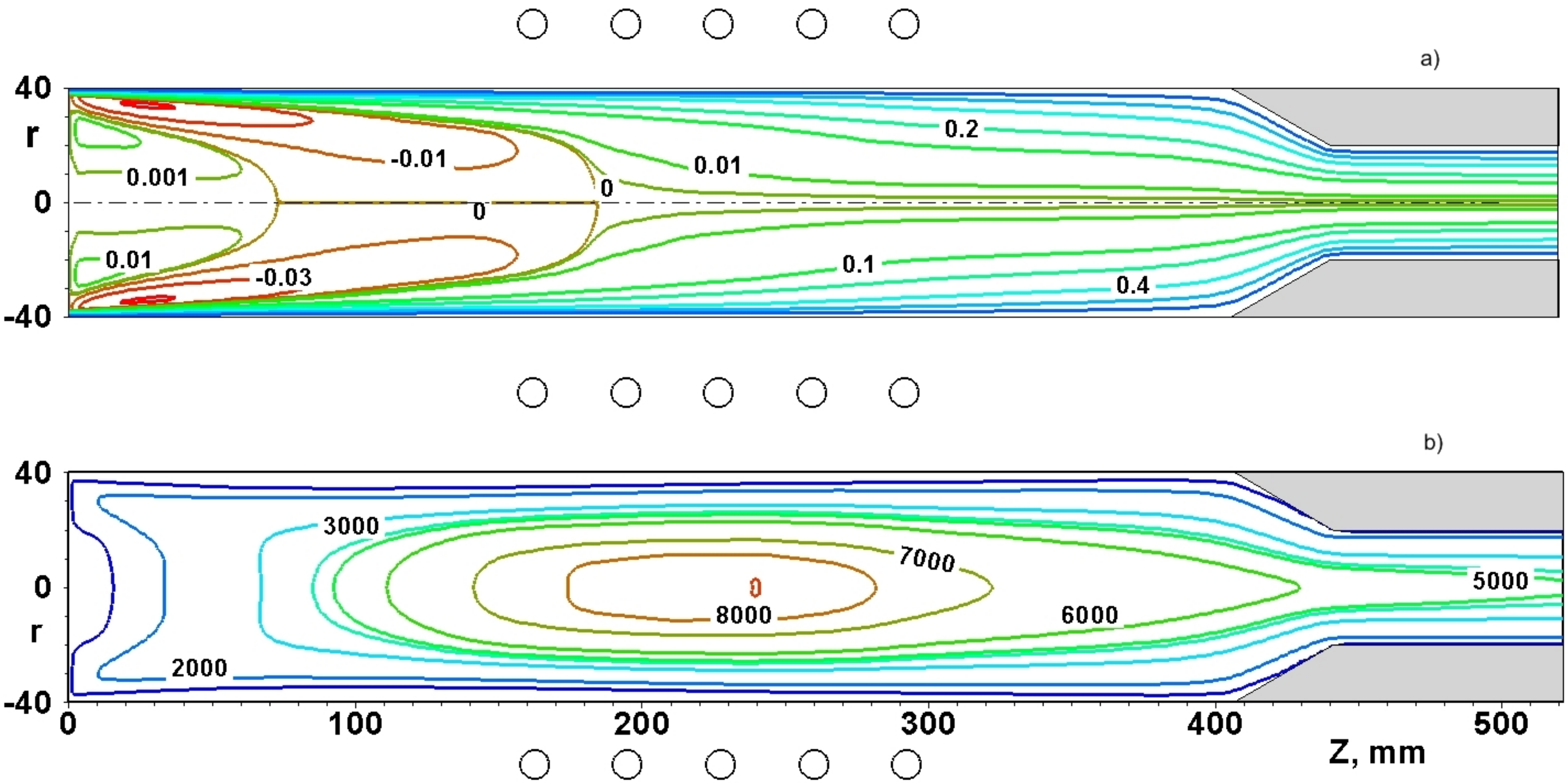
Enthalpy along subsonic jet

Heat fluxes to different materials at specified test conditions



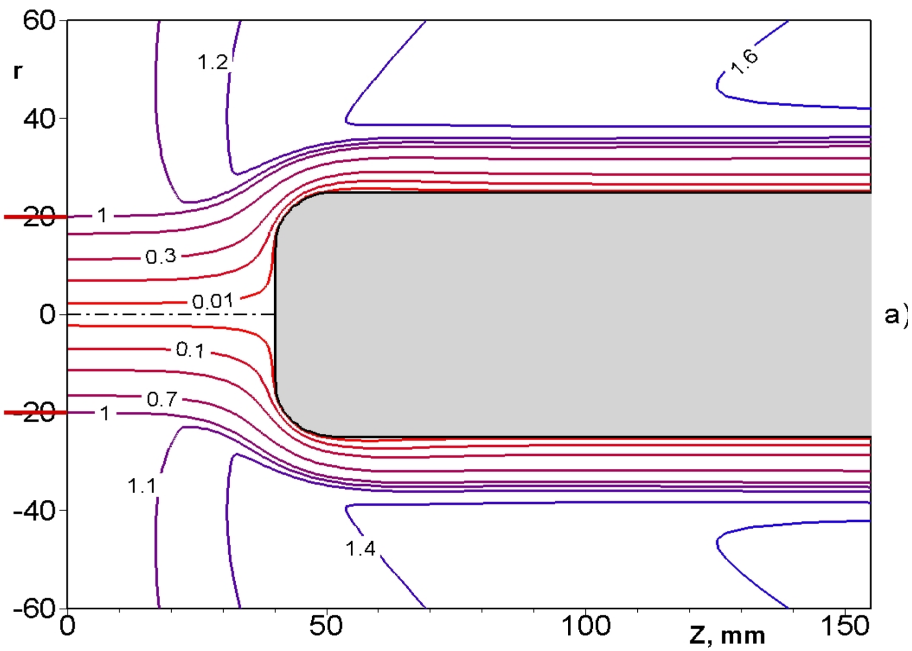
Heat flux vs anode power at p0 = 80 hPa, G=2.8 g/s

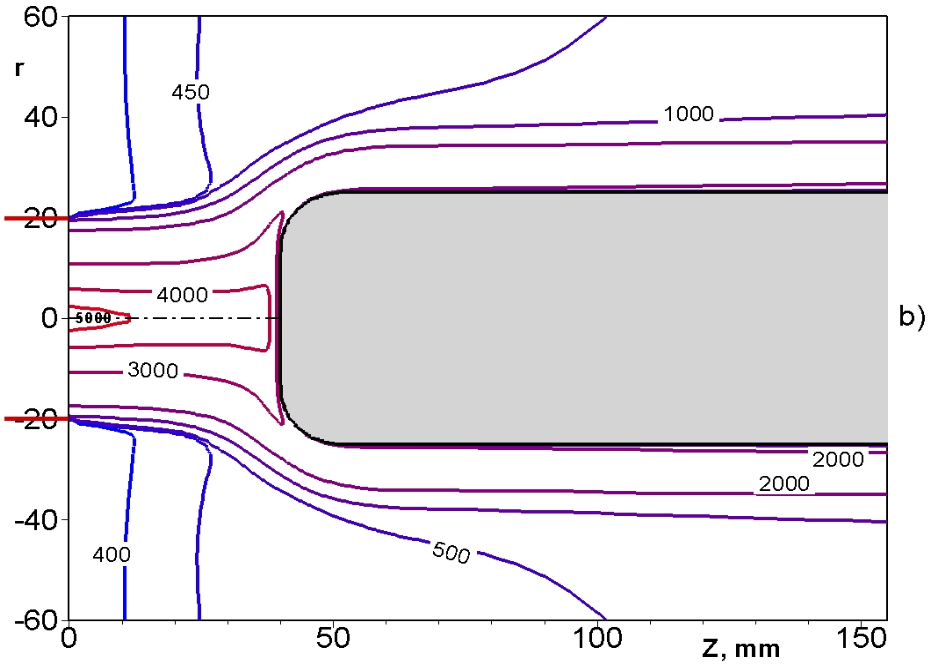
CFD modeling ICP flows (97%CO2 + 3%N2): isolines of stream function and isotherms



P=80 hPa, Npl=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:

$$O + S \rightarrow O\_S;$$
$$O + O\_S \rightarrow O_2 + S;$$
$$CO + O\_S \rightarrow CO_2 + S;$$

- 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

$$-J_O = \rho K_{WO} c_O + \frac{m_O}{m_{CO}} \rho K_{WCO} c_{CO}$$

$$-J_{CO} = \rho K_{WCO} c_{CO}$$

$$J_C = 0$$

$$J_{O_2} + \frac{2m_O}{m_{CO_2}} J_{CO_2} + \frac{m_O}{m_{CO}} J_{CO} + J_O = 0$$

$$K_{Wi} = \frac{2\gamma_{wi}}{2-\gamma_{wi}} \sqrt{\frac{R_A T_W}{2\pi m_i}}$$

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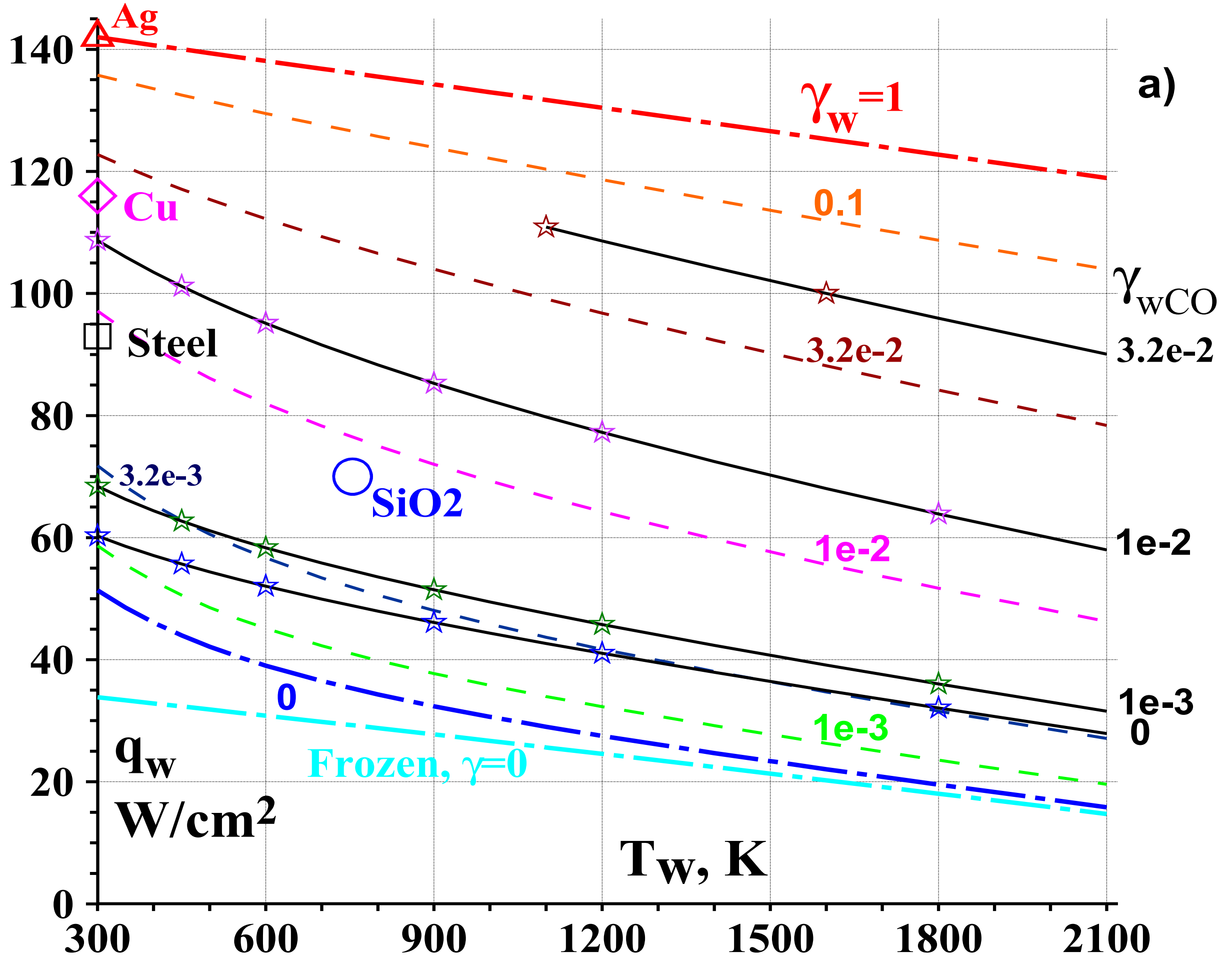
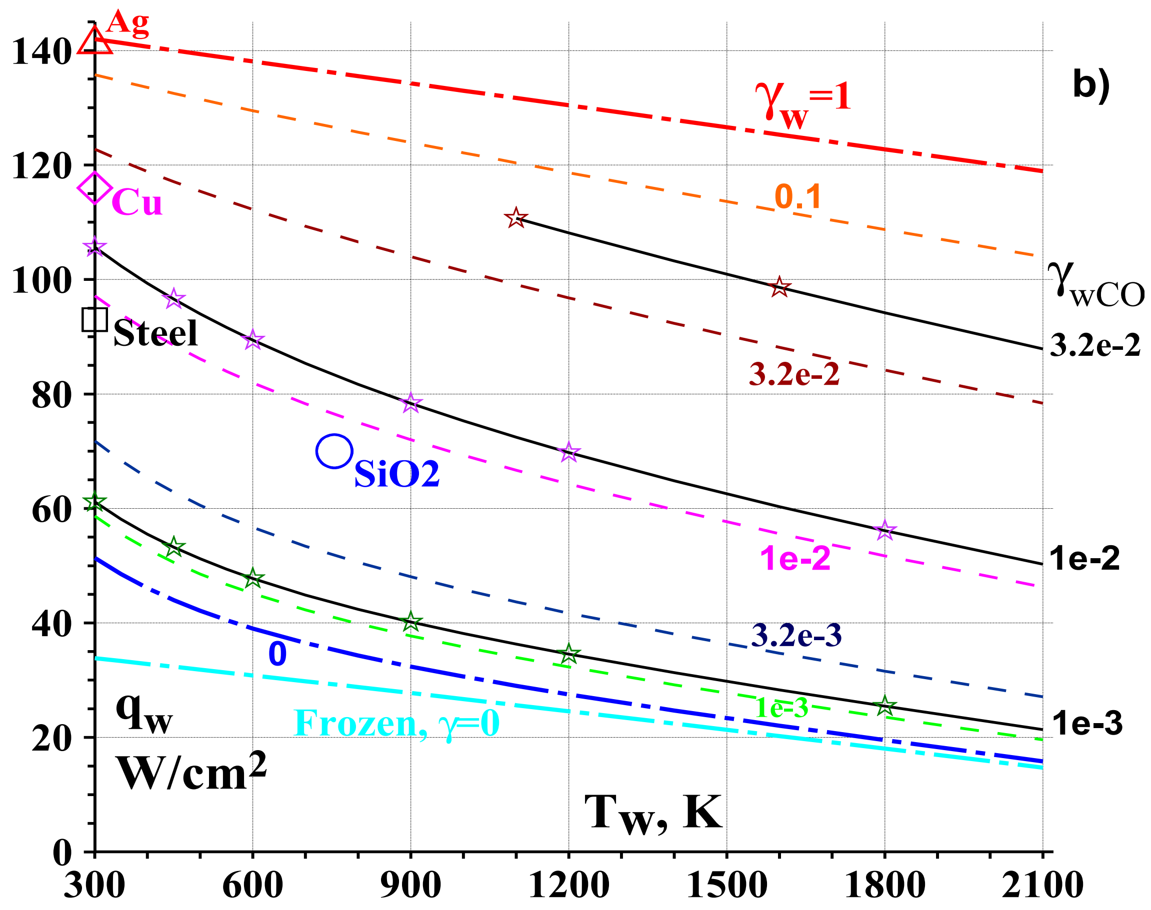
Heat flux envelopes for catalysis standard and new models



P=80 hPa, Nap=40.4 kW, he=14 MJ/kg, γ_{wO} =1e-2

Heat flux envelopes for catalysis standard and new models



P=80 hPa, Nap=40.4 kW, he=14 MJ/kg, ⍰wO =1e⍰3

Results of □co determination

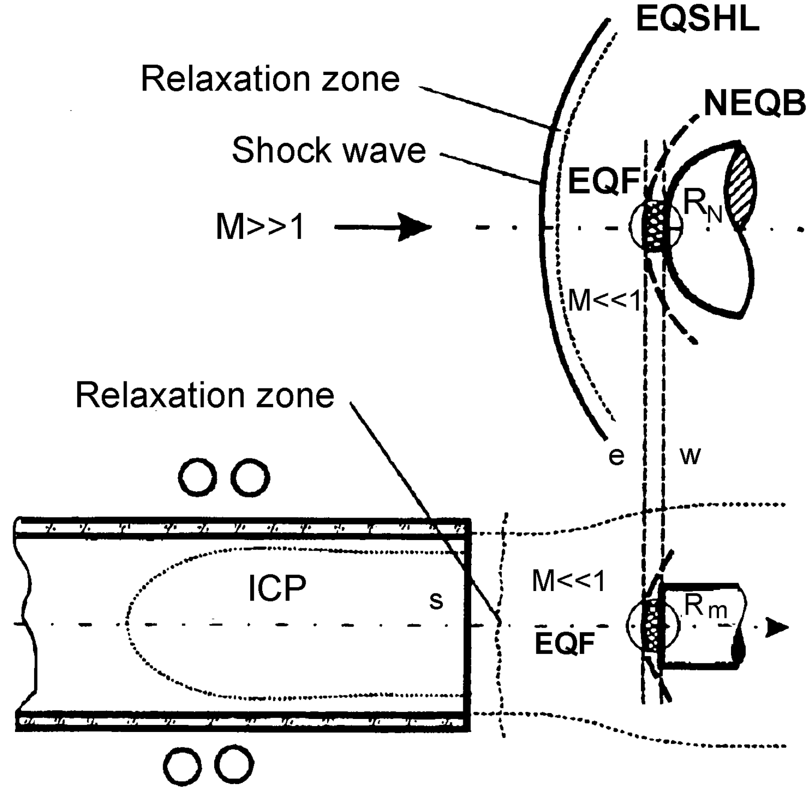
$$\square_w = \square_{wO} = \square_{wCO}$$

$\square_w$

P , hPa	material	Tw, K	q, W/cm^2	$\square_{wO}$ specified by literature data	$\square_{wCO}$ determined by novel model	$\square_w$ determined by standard model
80	quartz	755	70	2e□3	6.0e-3	7.84e-3
	steel	300	93	2.6e□3	6.1e-3	8.48e-3
80	quartz	600	45	2e□3	3e-3	4.97e-3
	steel	300	66	2.6e□3	n/a	1.07e-2

Extrapolation of heat transfer tests to re-entry conditions

- $H_{\square 2} = H_{\square 1}$
- $P_{02} = P_{01}$
- $(\square U/ \square s)_{e2} = (\square U/ \square s)_{e1}$
- 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

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

IPG-4	h_e, MJ/kg	p, hPa	V_S, m/s	R_m, m
I	14.0	80	357	0.025
II	8.8	80	286	0.025

Mars entry	V_∞, m/s	Z, km	R_N, m
I	5290	41.2	0.18
II	4200	38.1	0.16

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 γ_{O} and γ_{CO} on quartz and stainless steel surfaces predicted in subsonic dissociated CO_2 flows using standard and new models for surface catalysis

- Adsorption of CO molecules should be included in catalysis model for copper surface

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