Experimental and Numerical Simulation of Martian Entry Conditions

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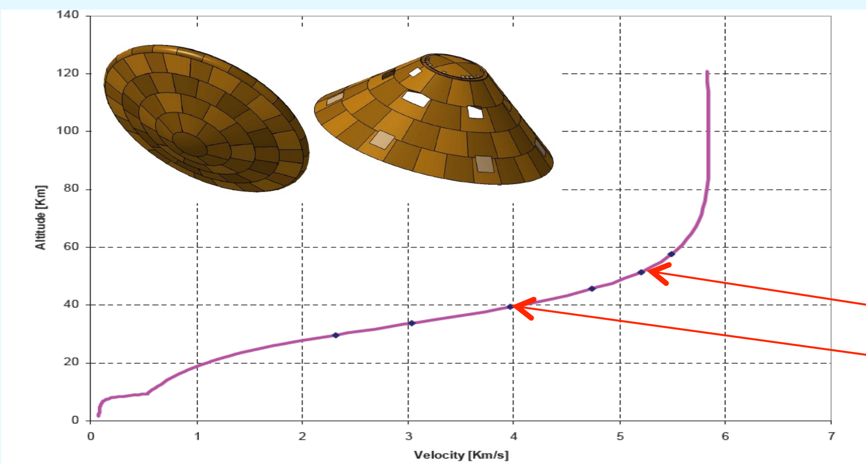
Outline

1. Work motivation and objectives
2. Test campaign
3. CFD rebuilding of tests
4. Conclusions

Work motivation and objectives(1)

Work objectives

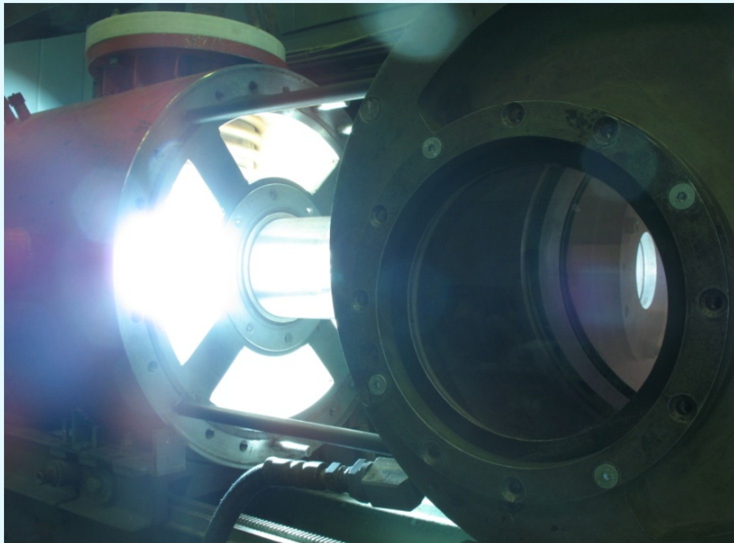
1. Experimental and numerical study of gas-surface interaction phenomena in the high enthalpy flow field behind the bow shock in front of a model at Martian entry flow conditions
2. Improvement of Mars atmosphere (97%CO_2) thermochemical model at high enthalpies
3. Obtaining new experimental data on physical and chemical behavior of Mars atmosphere species under highenthalpy flow conditions

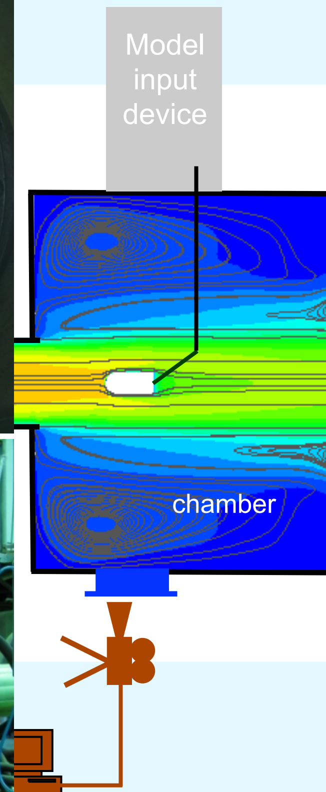


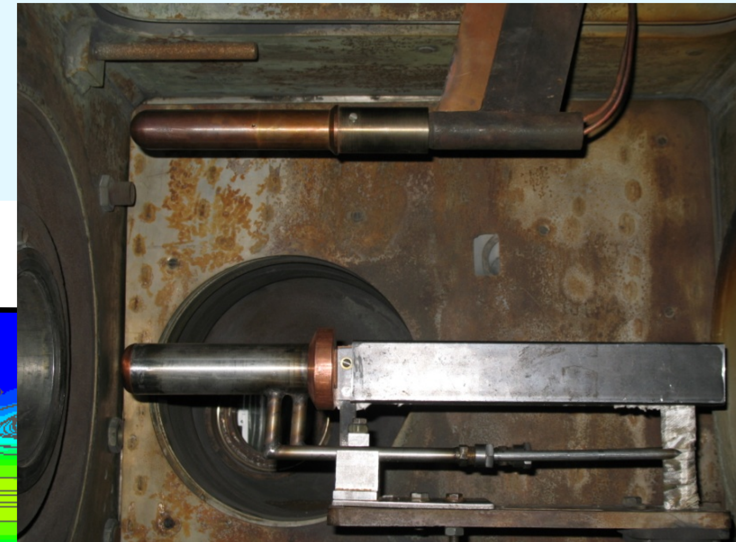
Reference points of the ExoMars trajectory used for experimental modeling in U-13 facility.

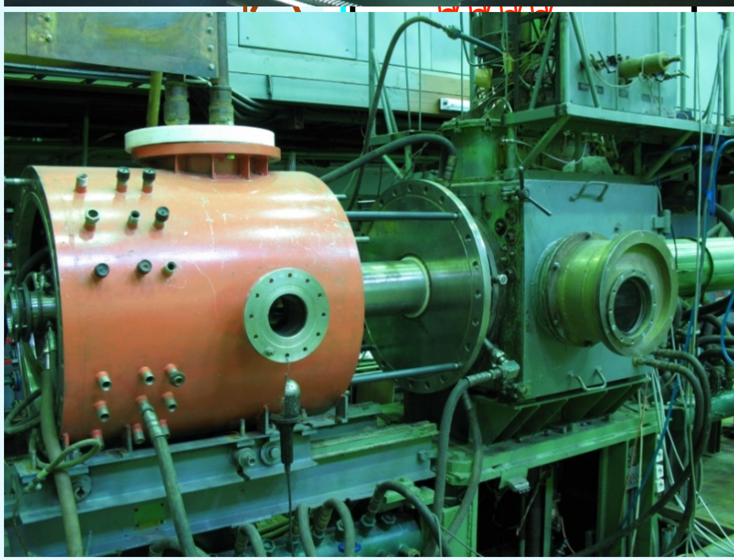
Trajectory point number	Time [sec]	Velocity [m/sec]	Enthalpy [MJ/kg]	Pitot pressure [hPa]
1	81	5228	13.8	55
2	104	4072	8.5	82

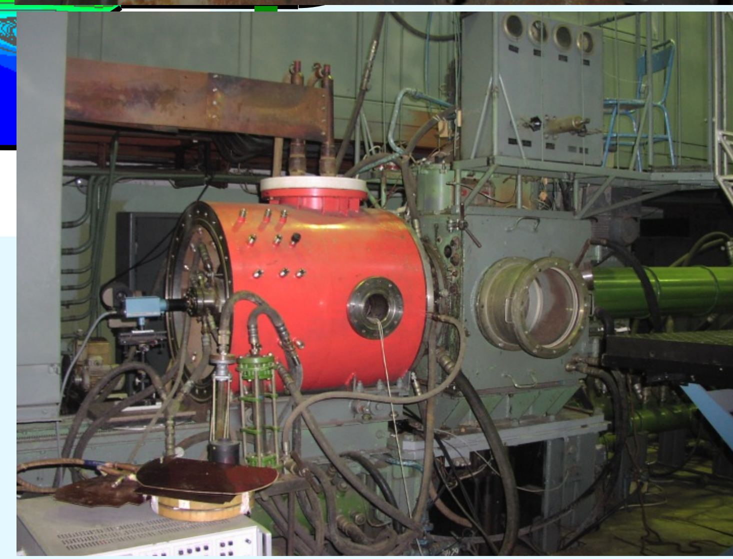
U-13 ICP facility



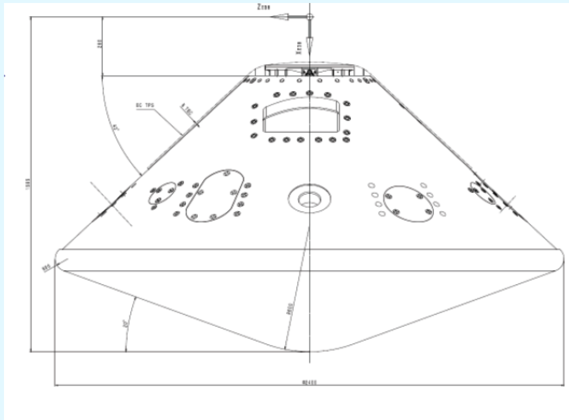


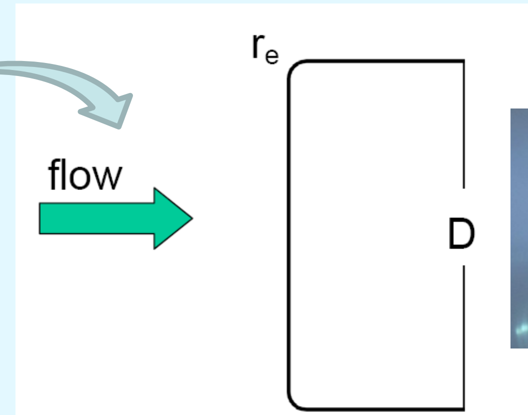


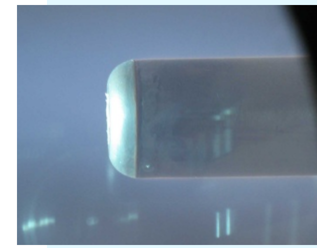




Test matrix



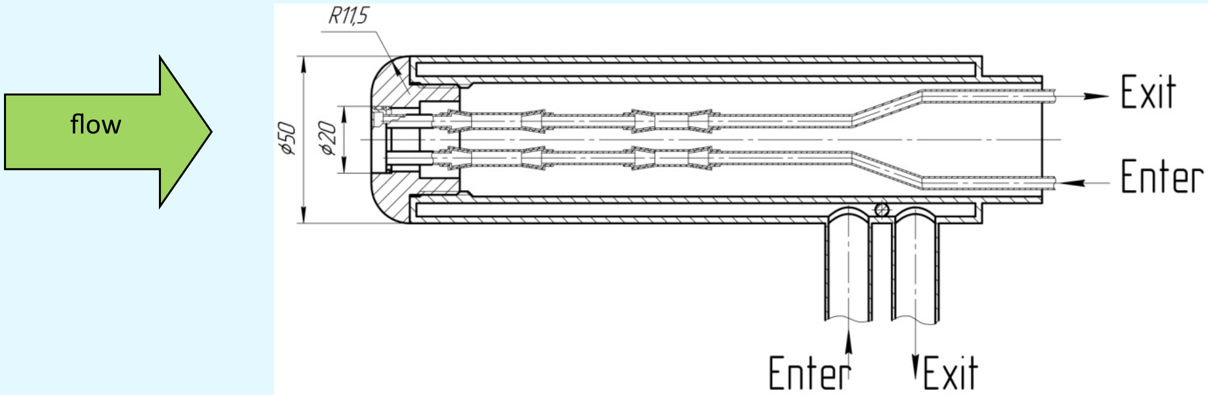




Test matrix for U-13 ICP facility

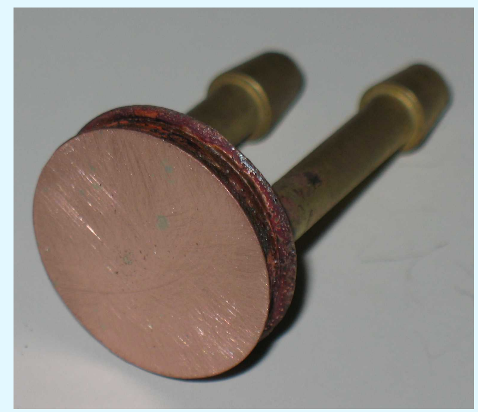
Test condition	Enthalpy [MJ/kg]	Pitot pressure [hPa]	Sample materials
FC1	13.8	10,20,40,80	Silver, Quartz,Copper
FC2	9	10,20,40,80	Silver, Quartz,Copper

Test model



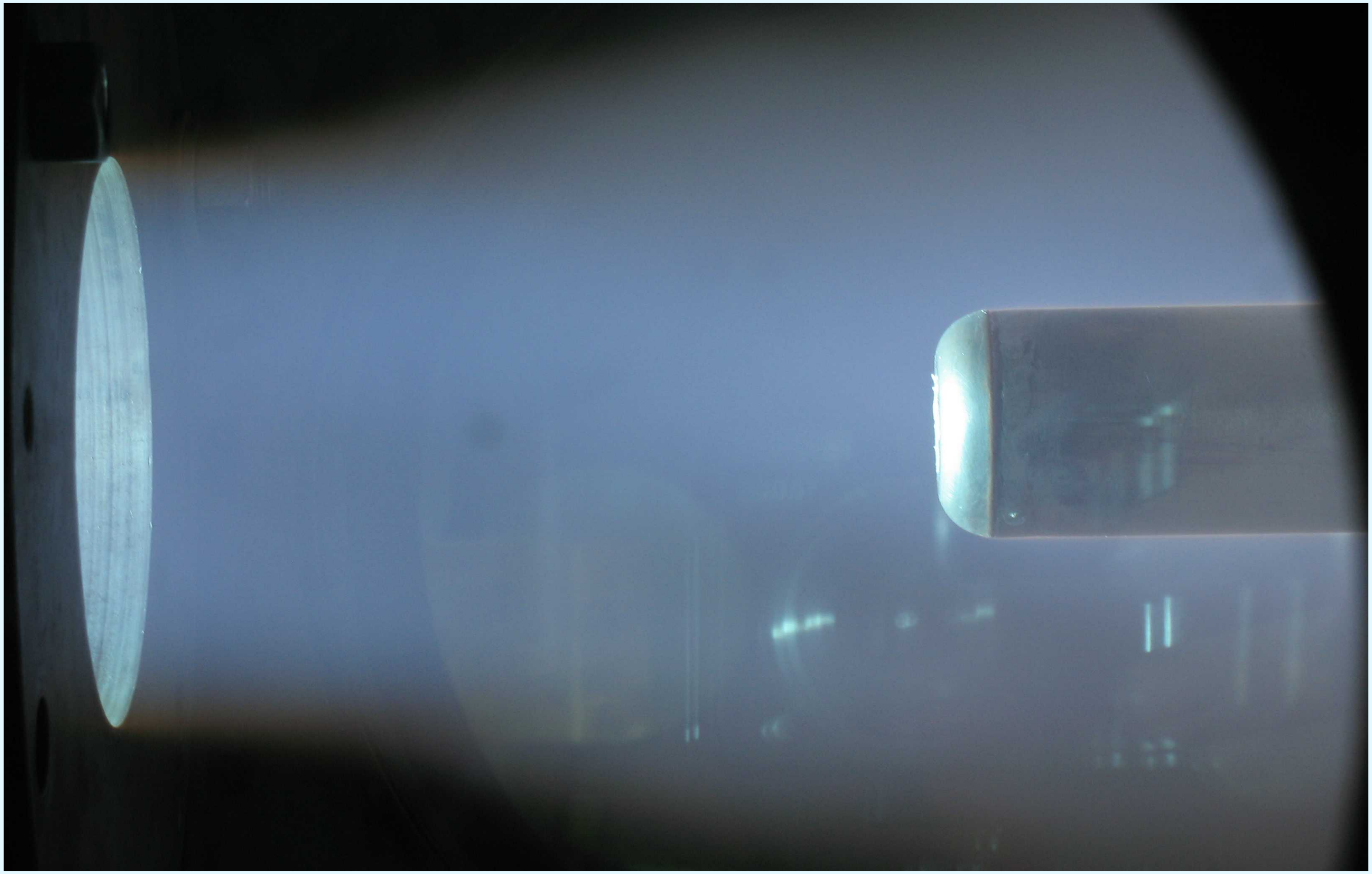
Silver calorimeter

Quartz calorimeter



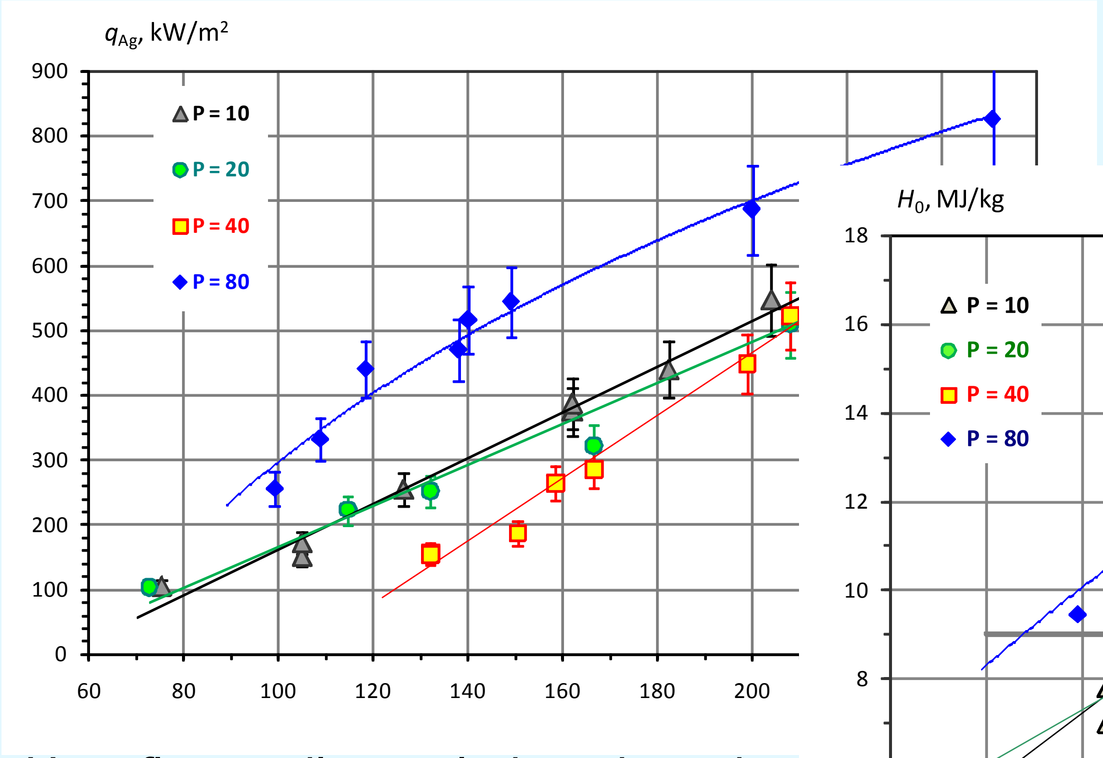
Copper calorimeter

Test model(2)

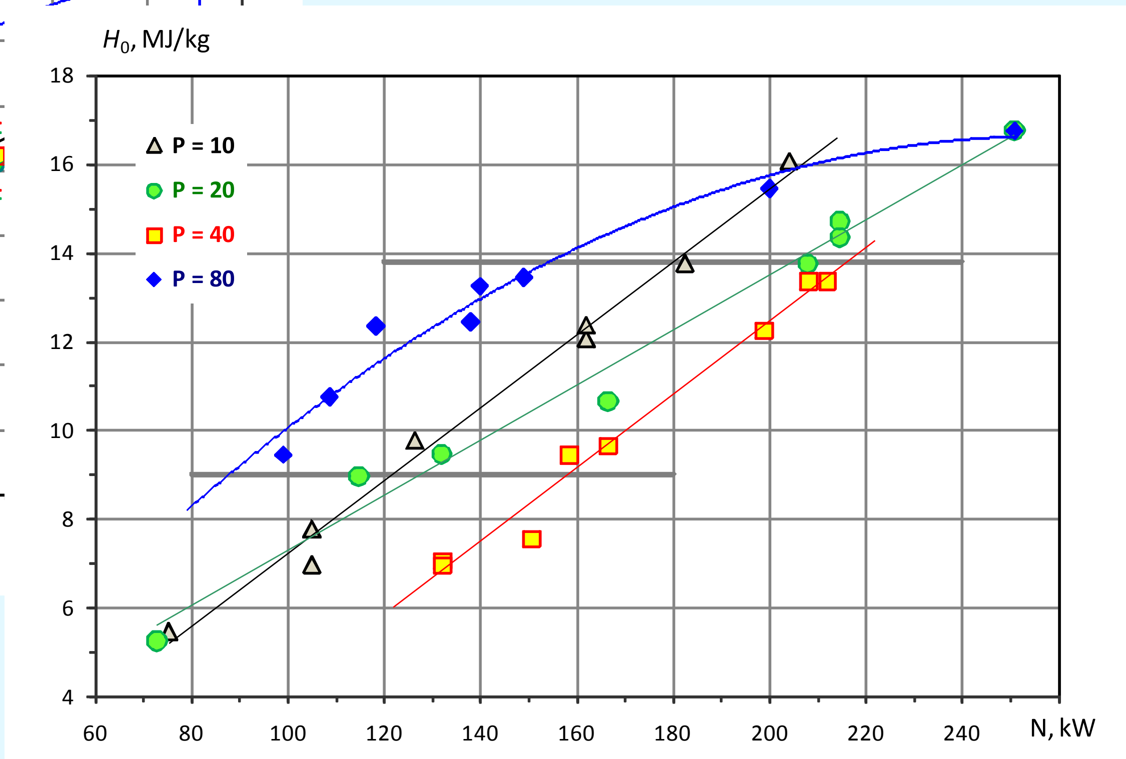


CO2+N2 mixture flow diagnostics in U-13 ICP facility

γ(O+O(s)) = 0.025
γ(CO+O(s)) = 0.05



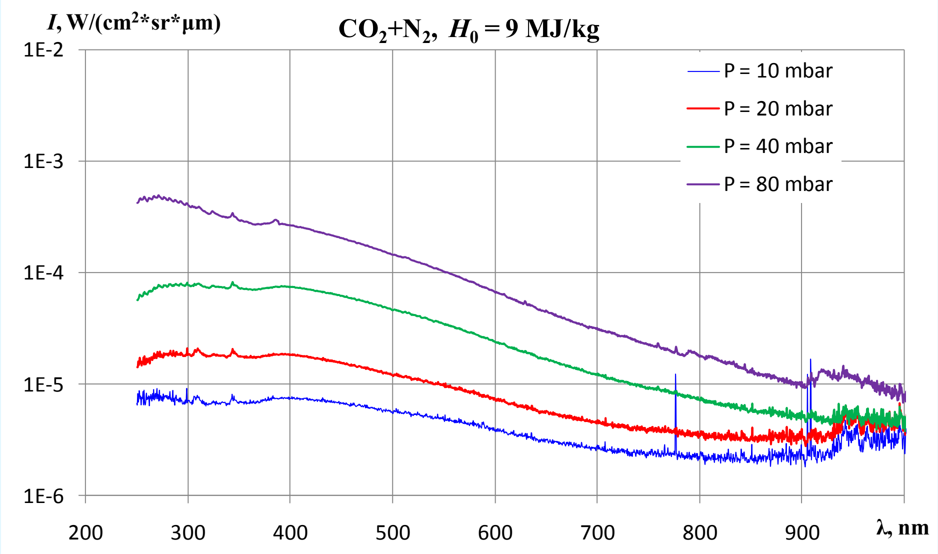
Heat flux to silver calorimetric probe

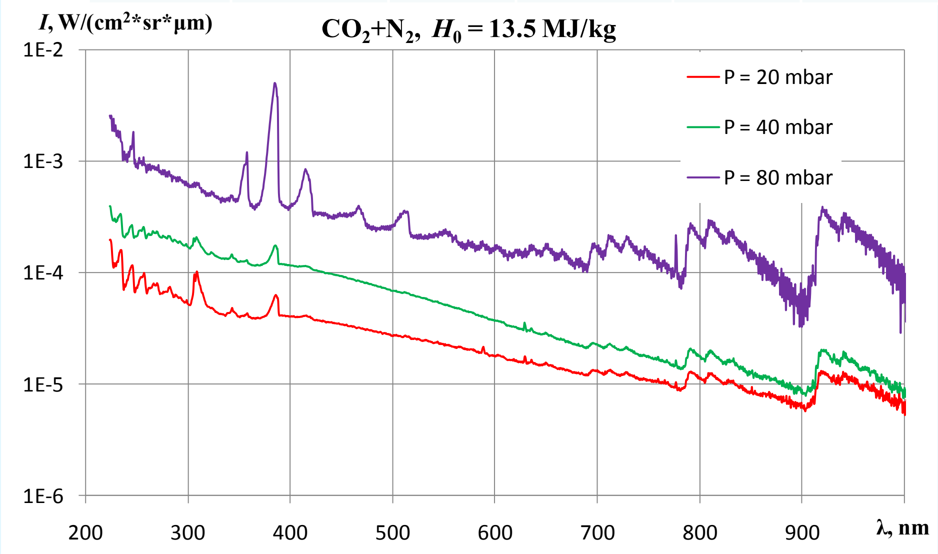


Total enthalpy vs. anode power

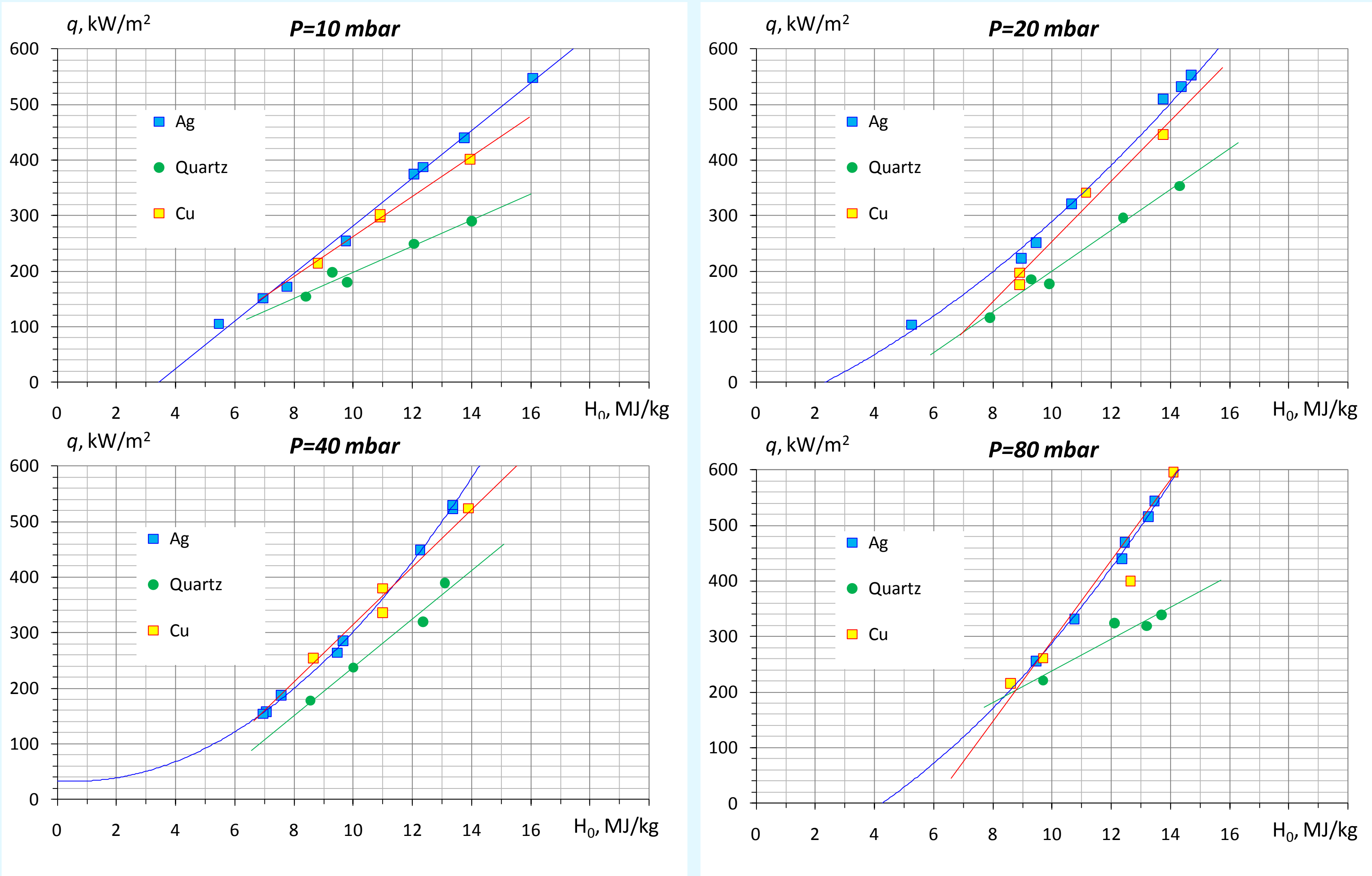
CO2+N2 mixture flow diagnostics in U-13 ICP facility (2)

P, hPa	H, MJ/kg	T,K	Line form	T,K	Abs
10	13.8	3000	OH(A)		
20	13.8	4000	CN(B)	3800-4400	CN(A,B) NO,O
40	13.8	4500	CN(B)	3800-4400	CN(A,B) NO,O
80	13.8	5000	CN(B)	4500-5000	CN(A,B) NO,O
40	9	3000	O2(SR)		
80	9	3000	O2(SR)		

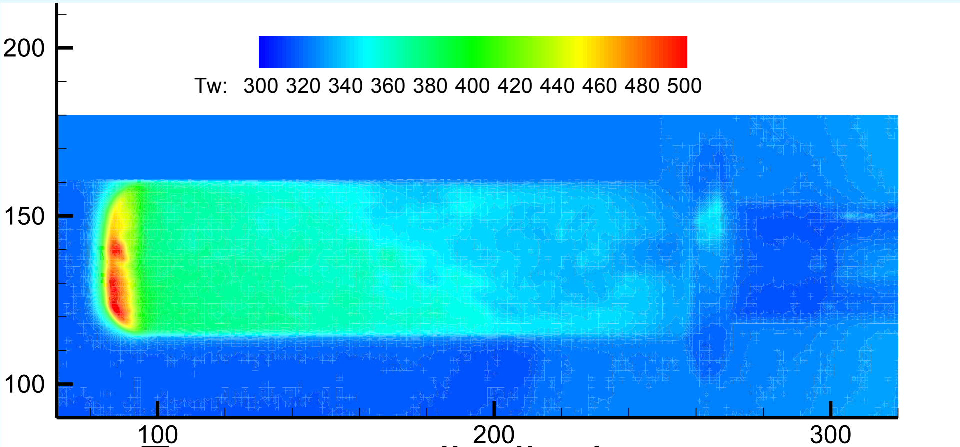




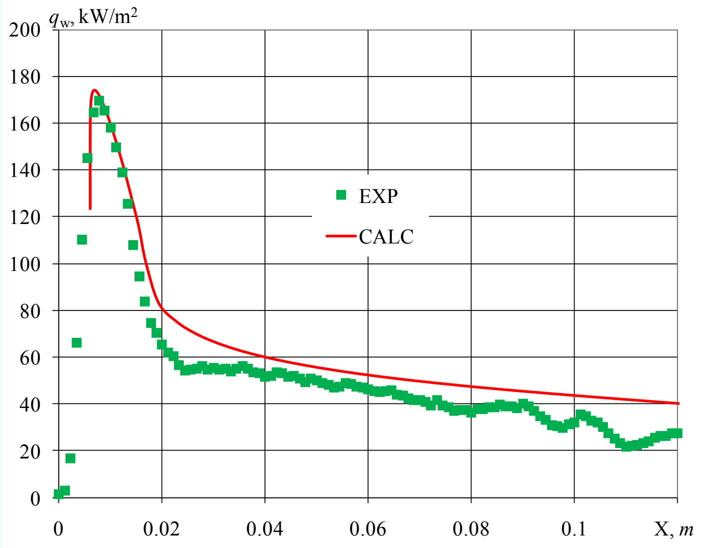
Test results

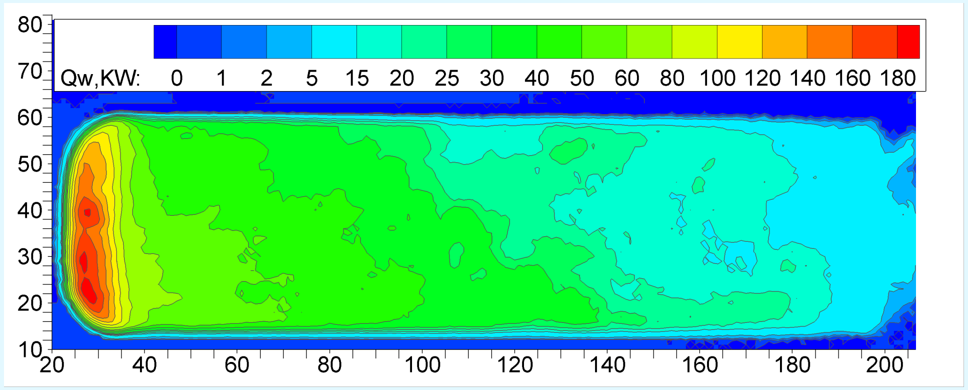


Test results



Temperature distribution,
t=1.2 s P=20 mbar, N=125 kW





Heat flux distribution

Governing equations

Continuity $$\frac{\partial}{\partial x}(y\rho u)+\frac{\partial}{\partial y}(y\rho v)=0$$

Momentum conservation

$$\frac{\partial}{\partial x}\left(y\left(\rho u^2+p-\tau_{xx}\right)\right)+\frac{\partial}{\partial y}\left(y\left(\rho uv-\tau_{xy}\right)\right)=yF_x$$

$$\frac{\partial}{\partial x}\left(y\left(\rho uv-\tau_{xy}\right)\right)+\frac{\partial}{\partial y}\left(y\left(\rho v^2+p-\tau_{yy}\right)\right)=p+\rho w^2-\tau_{\varphi\varphi}+yF_y$$

$$\frac{\partial}{\partial x}\left(y\left(\rho uw-\tau_{x\varphi}\right)\right)+\frac{\partial}{\partial y}\left(y\left(\rho vw-\tau_{y\varphi}\right)\right)=-\rho vw+\tau_{y\varphi}$$

$$\tau_{xx}=\mu\left(\frac{\partial u}{\partial x}-\tfrac{2}{3}\,\mathrm{div}\mathbf{U}\right),\quad \tau_{xy}=\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right),\quad \tau_{yy}=\mu\left(\frac{\partial v}{\partial y}-\tfrac{2}{3}\,\mathrm{div}\mathbf{U}\right),$$

$$\tau_{\varphi\varphi}=\mu\left(2\frac{v}{y}-\tfrac{2}{3}\,\mathrm{div}\mathbf{U}\right),\quad \tau_{x\varphi}=\mu\frac{\partial w}{\partial x},\quad \tau_{y\varphi}=\mu\left(\frac{\partial w}{\partial y}-\frac{w}{y}\right),$$

$$\mathrm{div}\mathbf{U}=\frac{\partial u}{\partial x}+\frac{1}{y}\frac{\partial(yv)}{\partial y}$$

Governing equations

Energy conservation

$$\frac{\partial}{\partial x}\left(y\left(\rho u H_0 - q_x\right)\right) + \frac{\partial}{\partial y}\left(y\left(\rho v H_0 - q_y\right)\right) = Q_J - Q_{rad} + \Phi$$

$$\Phi = \frac{\partial}{\partial x}\left(y\left(u\tau_{xx} + v\tau_{xy} + w\tau_{x\varphi}\right)\right) + \frac{\partial}{\partial y}\left(y\left(u\tau_{xy} + v\tau_{yy} + w\tau_{y\varphi}\right)\right),$$

$$\mathbf{q} = -\lambda_t \nabla T - \sum_m \lambda_{vm} \nabla T_{vm} - \lambda_e \nabla T_e + \sum_i \mathbf{J}_i h_i$$

Species continuity

$$\frac{\partial}{\partial x}\left(y\left(\rho u c_i - J_{ix}\right)\right) + \frac{\partial}{\partial y}\left(y\left(\rho v c_i - J_{iy}\right)\right) = y\dot{\omega}_i$$

$$\dot{\omega}_i = \sum_s \Delta\nu_{is}\left(k_{fs}\prod_j\left(\frac{\rho_j}{M_j}\right)^{\nu'_{js}} - k_{rs}\prod_j\left(\frac{\rho_j}{M_j}\right)^{\nu''_{js}}\right)$$

Maxwell equations

- Sine-wave EM-field (with frequency ω) :

$$\mathbf{E}=(0,0,E_\phi e^{-i\omega t}) \qquad \mathbf{B}=(B_x e^{-i\omega t}, B_r e^{-i\omega t}, 0)$$

- Ohm law $\mathbf{j}=\sigma\mathbf{E}$

$$E_{0\phi}(x,r)=\frac{4i\omega}{c^2}I_0\sqrt{\frac{a}{r}}\sum_{l=1}^{Nc}\left(\left(1-k_l^2/2\right)K(k_l)-E(k_l)\right),$$

- Inductor field:

$$k_l^2=\frac{4ar}{(a+r)^2+(x-x_l)^2},$$

- Total EM-field **E** is decomposed to the inductor (**E₀**) and plasma fields $\mathbf{e}=\mathbf{e}_1+i\mathbf{e}_2$ $\mathbf{E}=\mathbf{E}_0+\mathbf{e}$

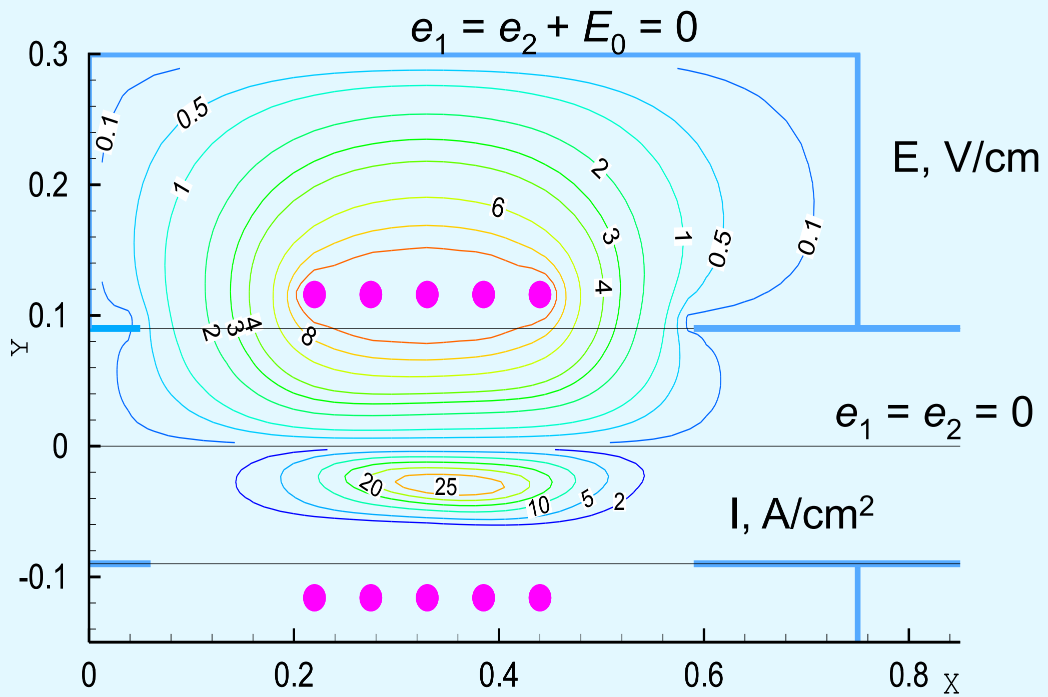
$$\frac{\partial^2 e_1}{\partial x^2}+\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial(re_1)}{\partial r}\right)-\frac{4\pi\omega}{c^2}e_2=\frac{4\pi\omega}{c^2}E_0,$$

$$\frac{\partial^2 e_2}{\partial x^2}+\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial(re_2)}{\partial r}\right)+\frac{4\pi\omega}{c^2}e_1=0.$$

- Lorentz force in motion equations $\mathbf{F} = \frac{1}{c}\mathbf{j}\times\mathbf{B}$

- Joule heating in energy equation $Q_J = \langle \mathbf{j}\cdot\mathbf{E}\rangle = \frac{1}{2}\sigma\left(e_1^2 + (e_2 + E_0)^2\right)$

- Either inductor current or energy input to plasma is imposed $Q_{pl} = 2\pi\int_0^R Q_J(x,r)\,r\,dr\,dx$



Thermochemical model

- CO_2+N_2 plasma (O_2, CO_2, CO, O, C,CO^+, NO^+, O^+,C^+, N^+, e^-,N_2,N,NO,CN)
- Reaction set

$O_2 + M_1 = O + O + M_1$ **$N_2 + M_4 = N + N + M_4$**
$CO_2 + M_2 = CO + O + M_3$ **$NO + M_5 = N + O + M_5$**
$CO + M_3 = C + O + M_2$ **$CN + M_6 = N + C + M_6$**
$O + CO = O_2 + C$ **$O + NO = O_2 + N$**
$O + CO_2 = O_2 + CO$ **$N + NO = N_2 + O$**
$O + C = CO^+ + e^-$ **$O + N = NO^+ + e^-$**
$O + e^- = O^+ + e^- + e^-$ **$N + e^- = N^+ + e^- + e^-$**
$C + e^- = C^+ + e^- + e^-$ **$CN + O = NO + C$**

- 1-temperature assumption ($T_{rot} = T_{vib} = T_e = T_{transl}$),
  2-temperature assumption ($T_{rot} = T_{transl}$, $T_{vib} = T_e$)
- Modified Fick's law (with account for ambipolar diffusion) - SCBD

$$\mathbf{J}_i = -\rho D_i \nabla c_i + \rho c_i \sum_j \left(D_j \nabla c_j \right)$$

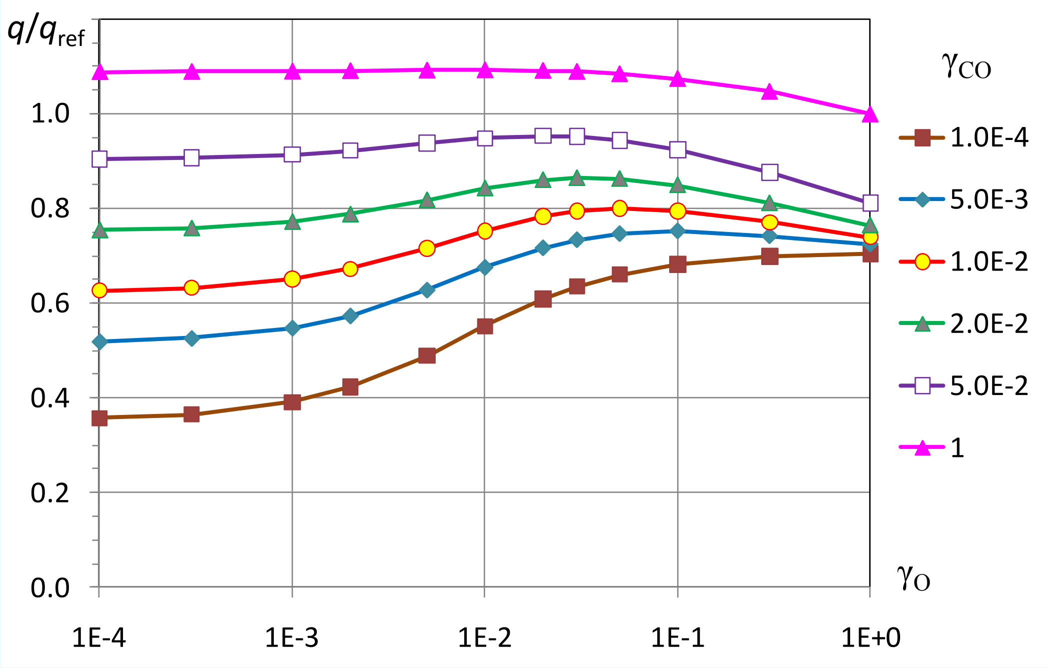
Thermochemical model

- Surface heterogeneous catalysis
- Surface reactions

$O_{(g)} \leftrightarrow (O\text{-}S)$ γ_{ads}

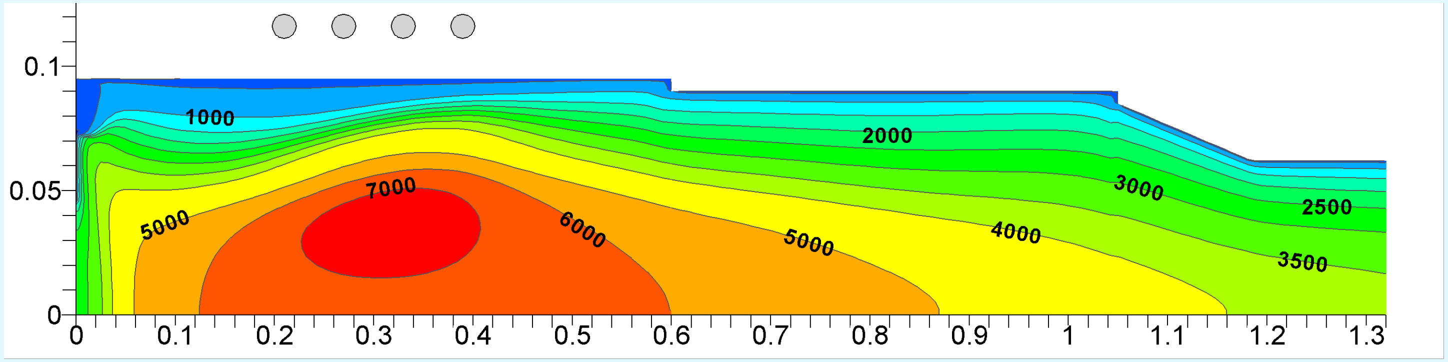
$O_{(g)} + (O\text{-}S) \rightarrow O_{2(g)}$ γ_{O}

$CO_{(g)} + (O\text{-}S) \rightarrow CO_{2(g)}$ γ_{CO}

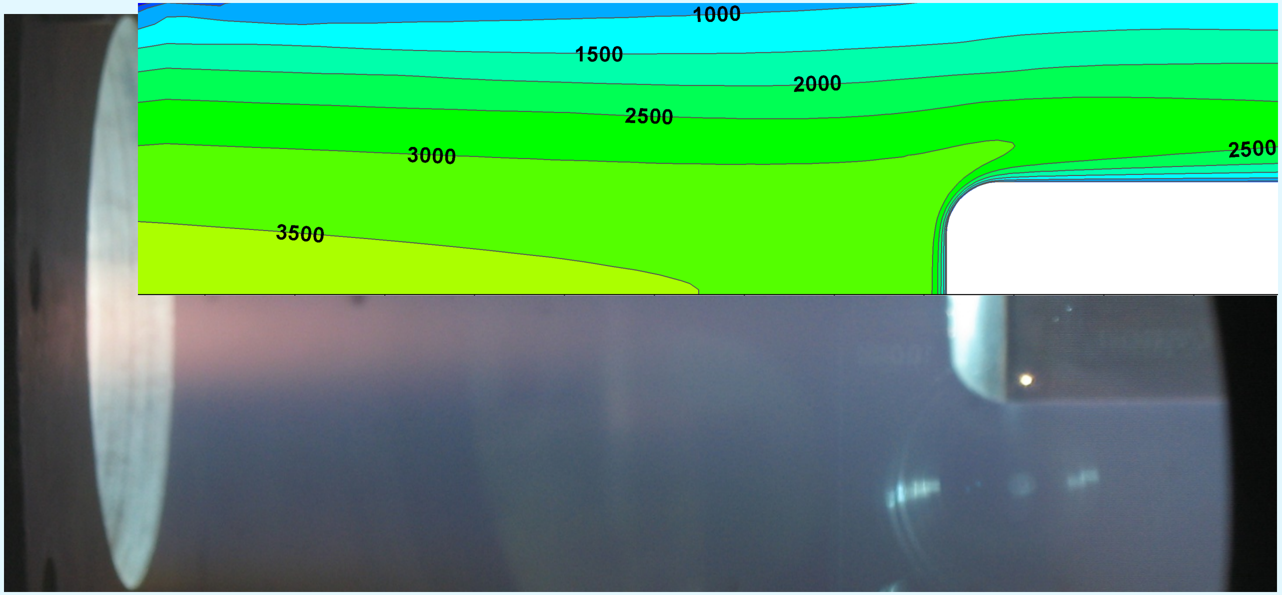


Relative heat flux depending on recombination probabilities at
P = 20 hPa, H0 = 17 MJ/kg
γ_{ads}= 0.2

Results of CFD test rebuilding

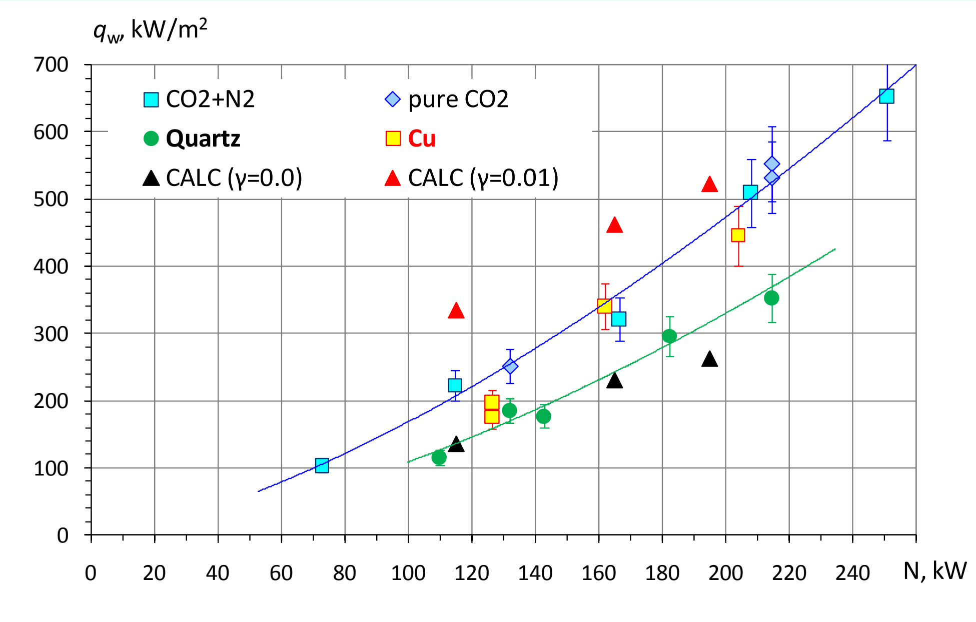


Temperature distribution within the discharge chamber , P=20 hPa, H=13.5MJ/kg

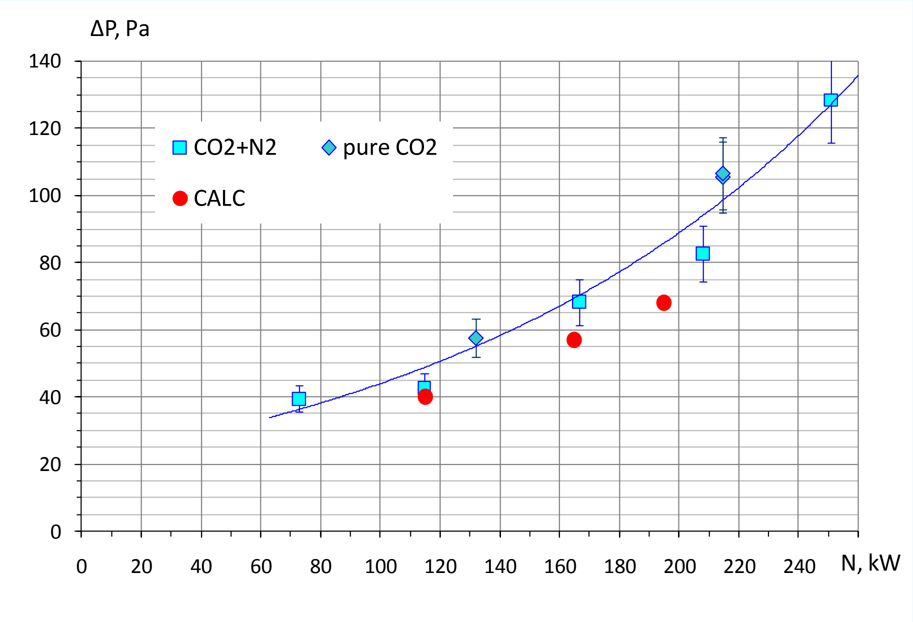


Temperature distribution in plasma jet near the model

Results of CFD test rebuilding



Experimental and numerical heat fluxes vs. input power at P = 20 hPa



Experimental and numerical Pitot pressure vs. input power at P = 20 hPa

Conclusions

✓A number of tests intended to investigate and improve thermochemical model of Martian atmosphere were performed in the U-13 ICP facility of TsNIImash. Measurements were made for two reference values of free stream enthalpy – 9 and 13.8 MJ/kg and four pressures – 10, 20, 40 and 80 hPa;

✓Heat fluxes to the silver, copper and quartz materials were measured;

✓Heat fluxes to the quartz surface is about 50% lower than to metallic surfaces;

✓Heat flux to the copper surface is only slightly lower than to the silver one;

✓Standard diagnostic procedure of ICP flow suitable for air flow conditions turns to be much more complicated and dependent on the thermochemical model for the case of CO_2;

✓Numerical rebuilding of the tests performed is in progress;

✓Preliminary results of CFD modelling demonstrates that silver (at least electrolysis coated) cannot be referred as fully catalytic material for CO_2+N_2 mixture species recombination for the test conditions;