Surzhikov Sergey, Andrienko Daniil
Institute for Problems in Mechanics
Russian Academy of Science, Moscow, Russia

Российская Академия Наук
Институт Проблем Механики РАН

# Aerothermodynamics of descent space vehicles at strong coupled radiative-gasdynamic interaction

## Foreword

- **Development of 2D and 3D CFD codes for investigation of aero– thermodynamics of space vehicles, intend for Martian Atmosphere**
- **Comparison of convective and radiative heating of surface SV (from the front stagnation point up to back one) for typical entering for Martian atmosphere conditions, particularly for single points of Pathfinder trajectory is considered**

## Governing system of equations

$$\frac{\partial\rho}{\partial t}+\mathrm{div}\,(\rho\mathbf{V})=0$$

$$\frac{\partial\rho u}{\partial t}+\mathrm{div}\,(\rho u\mathbf{V})=-\frac{\partial p}{\partial x}-\frac{2}{3}\frac{\partial}{\partial x}(\mu\,\mathrm{div}\mathbf{V})+\frac{1}{r}\frac{\partial}{\partial r}\left[r\mu\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial r}\right)\right]+2\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)$$

$$\frac{\partial\rho v}{\partial t}+\mathrm{div}\,(\rho v\mathbf{V})=-\frac{\partial p}{\partial r}-\frac{2}{3}\frac{\partial}{\partial r}(\mu\,\mathrm{div}\mathbf{V})+\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial r}\right)\right]+2\frac{\partial}{\partial r}\left(\mu\frac{\partial v}{\partial r}\right)+2\mu\frac{\partial}{\partial r}\left(\frac{v}{r}\right)$$

$$\rho c_p\frac{\partial T}{\partial t}+\rho c_p\mathbf{V}\,\mathrm{grad}\,T=\mathrm{div}\,(\lambda\,\mathrm{grad}\,T)+\frac{\partial p}{\partial t}+\mathbf{V}\,\mathrm{grad}\,p+\mu\left[2\left(\frac{v}{r}\right)^2+2\left(\frac{\partial v}{\partial r}\right)^2+2\left(\frac{\partial u}{\partial x}\right)^2\right]+\mu\left[\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial r}\right)^2-\frac{2}{3}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial r}+\frac{v}{r}\right)^2\right]-\mathrm{div}\,\mathbf{q}_R-\sum_{i=1}^{N_s}h_i\dot{w}_i+\sum_{i=1}^{N_s}\rho c_{p,i}D_i\,(\mathrm{grad}\,Y_i\cdot\mathrm{grad}\,T)$$

$$\frac{\partial\rho_i}{\partial t}+\mathrm{div}\,\rho_i\mathbf{V}=-\mathrm{div}\,\mathbf{J}_i+\dot{w}_i,\quad i=1,2,\ldots,N_s$$

$$\frac{\partial\rho_m e_{v,m}}{\partial t}+\mathrm{div}\,(\rho_m\mathbf{V}e_{v,m})=\dot{e}_{v,m},\quad m=1,2,\ldots,N_V$$

$$W_i=\sum_{n=1}^{N_r}\left(\frac{dX_i}{dt}\right)_n=\sum_{n=1}^{N_r}\left(k_{f,n}\,(b_{i,n}-a_{i,n})\prod_j^{N_s}X_j^{a_{j,n}}\right)-\sum_{n=1}^{N_r}\left(k_{r,n}\,(b_{i,n}-a_{i,n})\prod_j^{N_s}X_j^{b_{j,n}}\right)$$

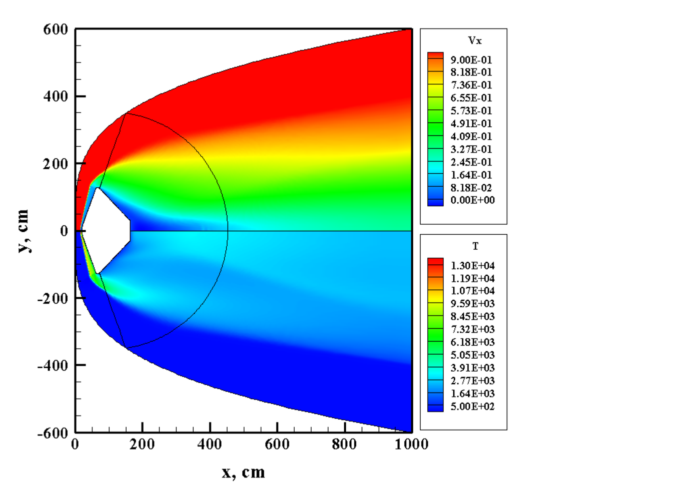
$$\mathbf{\Omega}\frac{\partial J_\omega(\mathbf{r},\mathbf{\Omega})}{\partial\mathbf{r}}+\kappa_\omega(\mathbf{r})J_\omega(\mathbf{r},\mathbf{\Omega})=j_\omega(\mathbf{r})$$

$$j_\omega(\mathbf{r})=\kappa_\omega(\mathbf{r})J_{b,\omega}(\mathbf{r})$$

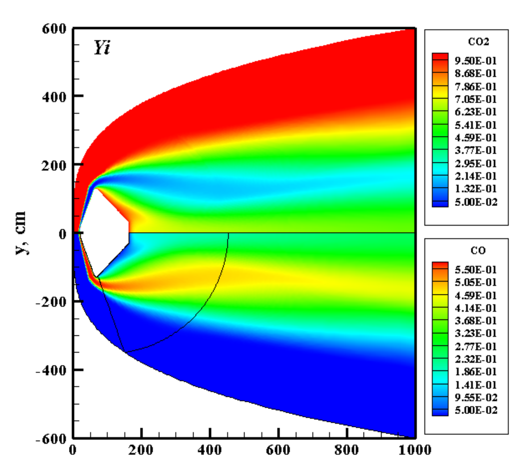
## Nomenclature

$t$ - time; $u,v$ – velocity $\mathbf{V}$ $x$-projection and $r$-projection; $p$, $\rho$ - pressure and density; $\mu$ - viscosity dynamic coefficient, $T$ – translational particle motion temperature; $\lambda$ - heat conductive coefficient; $c_p=\sum_i^N Y_i c_{p,i}$ - specific mixture heat capacity at constant pressure; $Y_i=\rho_i/\rho$ - mass fraction of $i$-mixture component; $c_{p,i}$, $h_i$, $\rho_i$ - specific heat capacity at constant pressure, enthalpy and density of $i$ mixture component; $\dot{w}_i$ - chemical transformation mass rate for $i$-mixture component; $D_i$ - diffusion coefficient of $i$-mixture component; $J_i$ - diffusion flux density of $i$-mixture component $J_i=-\rho D_i\,grad\,Y_i$; $N_i$ - number of chemical gas mixture components; $e_{v,m}$- specific vibrational energy of $m$-vibrational mode $\rho_m$ - molecules density at $m$-vibrational mode); $\dot{e}_{v,m}$- the specific vibrational $m$-mode changing rate (due to vibrational-translational (VT) energy exchange and dissociation and recombination process), $a_{i,n}$, $b_{i,n}$ - stoichiometric coefficients of $n$-chemical reaction at generalized formulation, $X_i$ - volume-molarity concentration of $i$-component; $[X_j]$ - chemical symbol of chemical reaction reagents and products; $N_r$ - number of chemical reactions; $k_{f,n}$, $k_{r,n}$ - rate constant of forward and backward reactions, $J_\omega(r,\Omega)$ - the spectral intensity of radiation; $\kappa_\omega(r)$ - spectral absorption coefficient; $j_\omega(r)$ - spectral emitting coefficient, calculated through Kirchhoff law (under local thermodynamic assumption). $J_{b,\omega}(r)$ - black body intensity of radiation (the Plank function); $r$ – radius-vector of current spatial coordinate; $\Omega$ - unit vector along direction of radiation propagation.

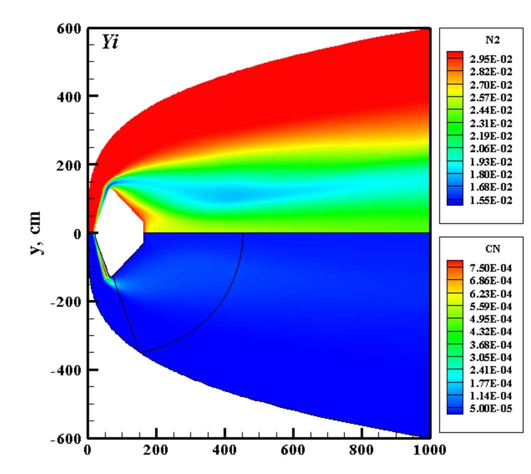
## Pathfinder



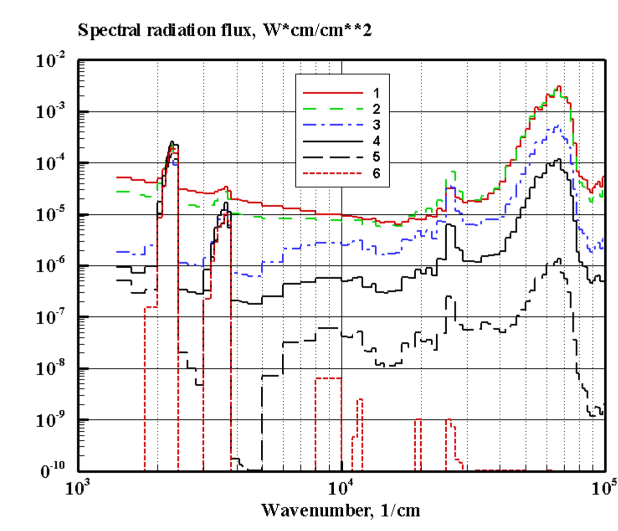
Longitudinal velocity and temperature



$CO_2$ and CO mass fractions

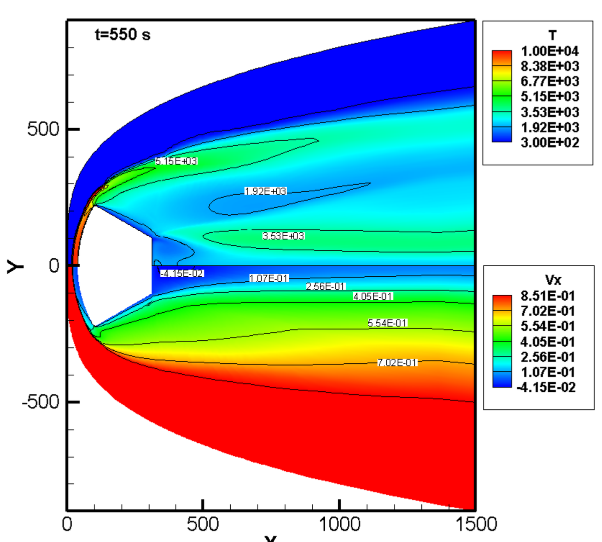


$N_2$ and CN mass fractions

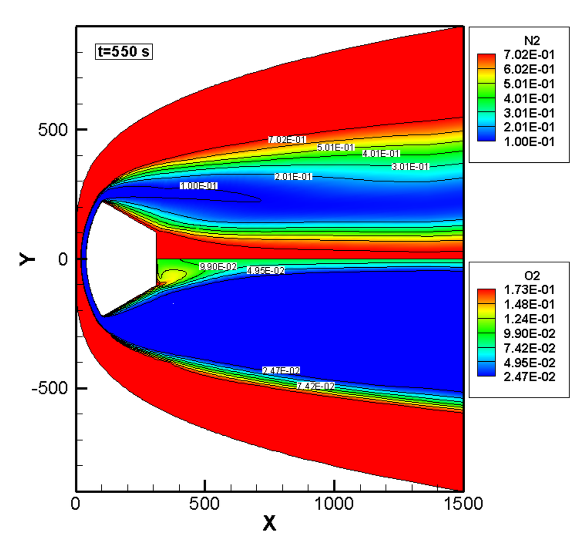



Spectral radiation flux for different surface points

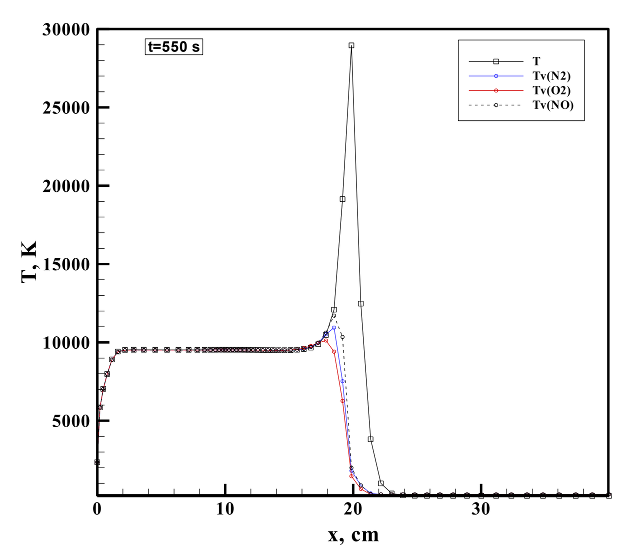
## **Luna** segmental-cone space craft



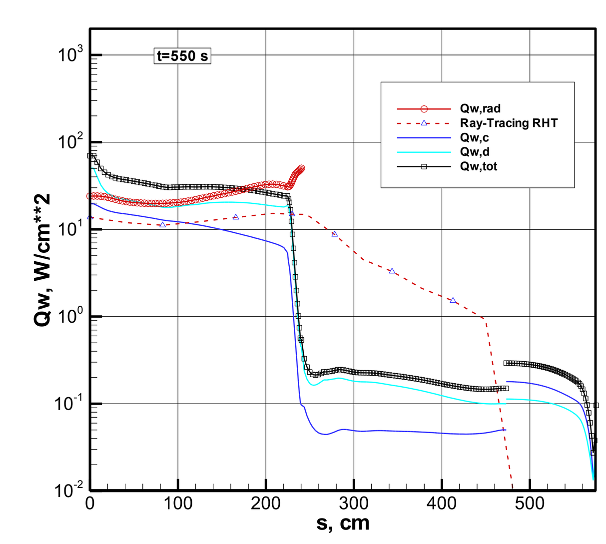
Flow field, velocity at entering in Earth atmosphere $V_{ini}$=10.524 m/s at altitude $H$=140 km. Trajectory point $t$=550 s. Upper half: translational temperature, K. Down half: longitudinal velocity $V_x=u/V_*$ $V_*$=0.10400E+07 cm/s.



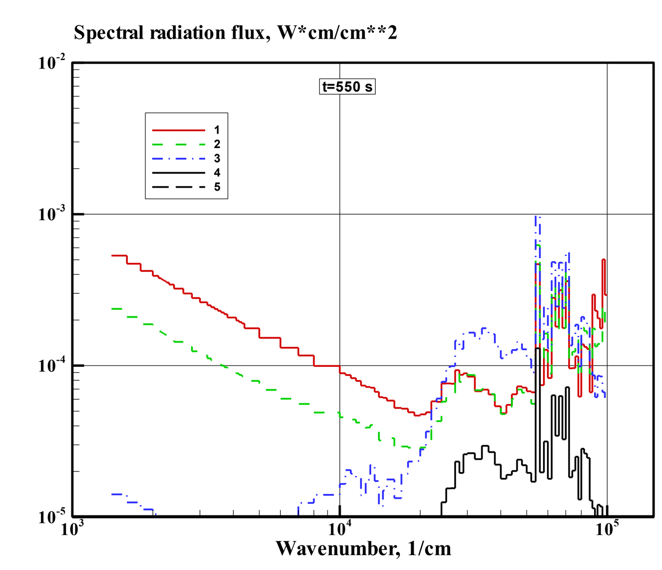
Flow field, velocity at entering in Earth atmosphere $V_{ini}$=10.524 m/s at altitude $H$=140 km. Trajectory point $t$=550 s. Upper half: weight fraction $N_2$. Down half: weight fraction $O_2$



Flow field, velocity at entering in Earth atmosphere $V_{ini}$=10.524 m/s at altitude $H$=140 km. Trajectory point $t$=550 s. Axial distribution of translational and vibrational temperature along front crucial line, K

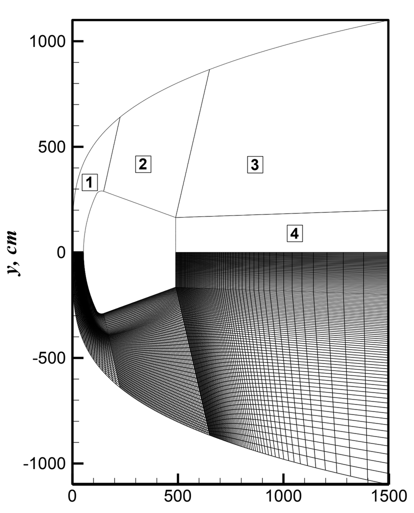


Flow field, velocity at entering in Earth atmosphere $V_{ini}$=10.524 m/s at altitude $H$=140 km. Trajectory point $t$=550 s. Distribution of convective flux density ($Q_{w,tot}$, $Q_{w,c}$, $Q_{w,d}$ ) and radiative flux density ($Q_{w,rad}$ , Ray-tracing RHT)) along surface W/cm$^2$

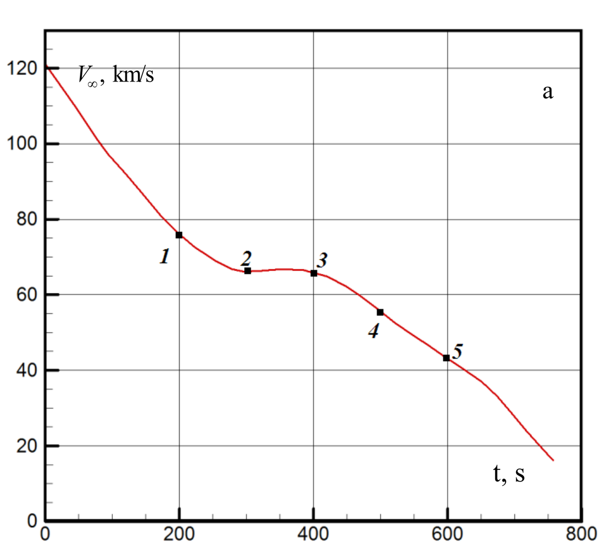


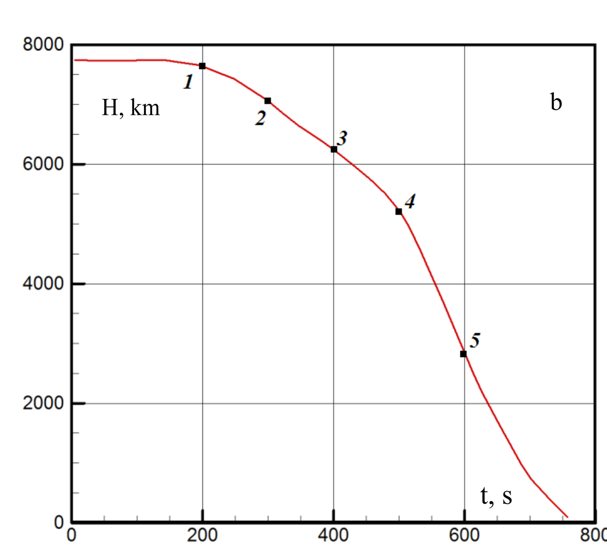

Flow field, velocity at entering in Earth atmosphere $V_{ini}$=10.524 m/s at altitude $H$=140 km. Trajectory point $t$=550 s. The spectral distribution of radiative flux at different points of surface. Calculations are carried out with Ray-tracing method, W·cm/cm$^2$. Numbers 1-5 correspond to different surface point

## ORION International Space Station Crew Exploration Vehicle (ISS CEV)

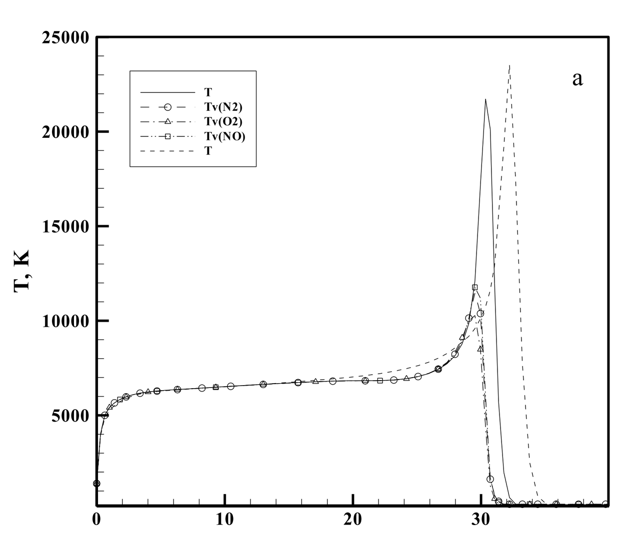


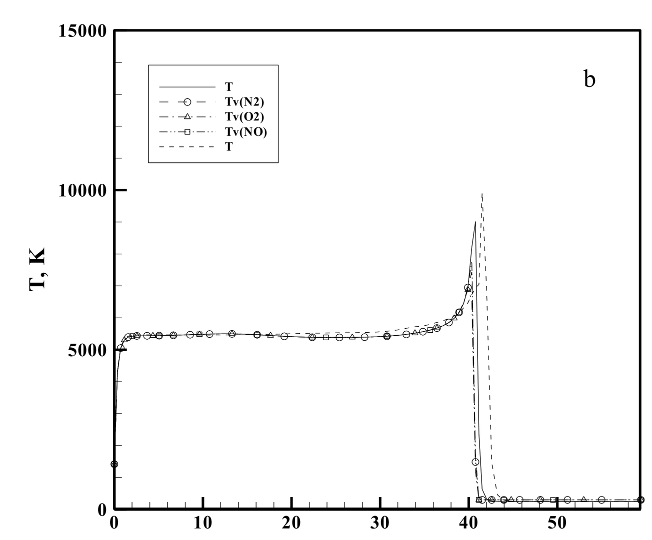
Computational domain and structured mesh, subdomains are marked with numbers (1-4)





Decent trajectory of space vehicle ISS CEV: (a) - velocity, (b) – altitude

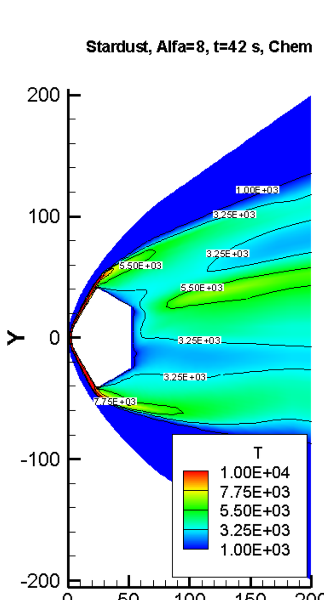




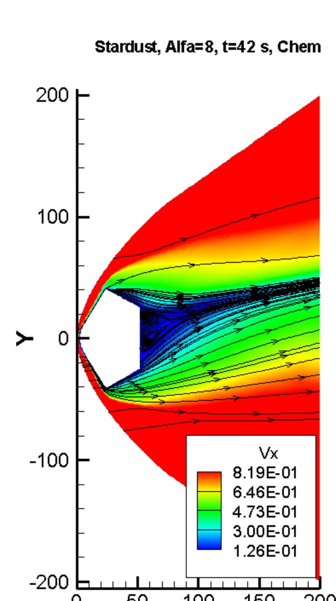
Translational and vibrational temperature distribution along front crucial line of CEV for the first (a) and fourth (b) trajectory points; Dashed line – temperature distribution in compressed layer without radiative-gasdynamic interaction

## STARDUST, American interplanetary mission of the NASA Jet Propulsion Laboratory

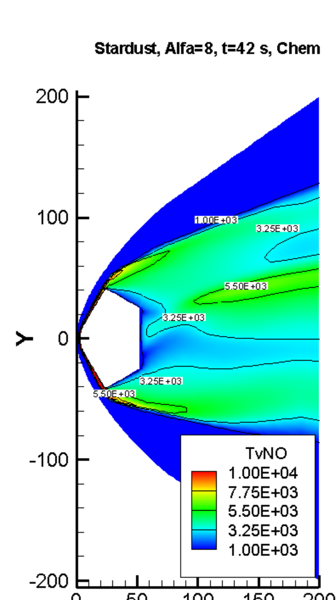
The Stardust capsule with cometary and interstellar samples landed at the U.S. Air Force Utah Test and Training Range



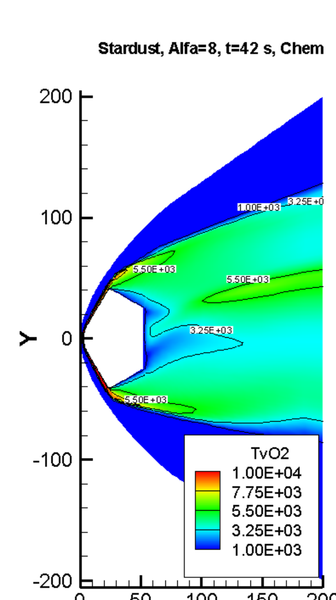
Temperature distribution



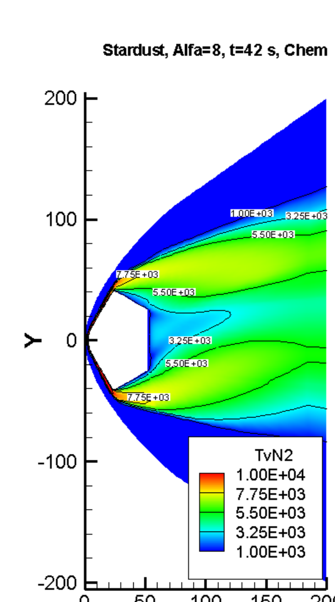
Longitudinal velocity



Vibrational temperature, NO



Vibrational temperature, $O_2$



Vibrational temperature, $N_2$

## Remarks and conclusion

- The numerical-theoretical calculation of space vehicles (SV) radiative-convective heat exchange in the $CO_2$-$N_2$ atmosphere for heat-stressed points of trajectory is performed.
- The distributions of radiative and convective fluxes along space vehicle surface at trajectory point corresponded to entering in Martian atmosphere at disequilibrium conditions are found out. At separate trajectory parts of SV entering in $CO_2$ atmosphere the radiation heating may exceed convective heating. The analysis of radiation flux value along the whole Martian SV surface is strongly required.
- The analysis of spectral radiative flux to surface was performed. For this purpose the distribution of absorbing and emitting ability within the shock layer near front crucial line and in trace of flowing body was studied. The radiative heating under considered conditions is conditioned by emitting in electronic bands of CO (fourth positive system of bands and band Hopfield-Burge) and rotational-vibrational $CO_2$ bands.
- Calculations are made under assumption of local thermodynamic equilibrium. The significant part of Martian SV trajectory are hold in rarefied atmosphere, so the future code development is to be taken into account.

## Sponsors

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- The values of radiative and convective flux used for shock wave tube experiments planning in Laboratory of Physical Kinetics of MIPT (project RFBR № 10-01-00468) and Lomonosov's Research Institute of Mechanics (project RFBR № 09-08-00272).

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