Radiative Gas Dynamics - II

Sergey T. Surzhikov
Institute for Problems in Mechanics
Russian Academy of Sciences
Radiative Gas Dynamics

Part I

Theoretical basis and general definitions

Part II

Numerical simulations of aerospace RGD applications
Outline

1. MHD/RGD governing equations
2. Laser Plasma Aerodynamics
3. 3D MHD numerical simulation of Hall plasma thruster plume
4. Safety rescue systems for astronauts and payload
5. Non-equilibrium radiation of shock waves
6. Entry and Re-Entry hypersonics
7. Modern challenging problems of RGD and on-going efforts
Block-diagram of the Radiative Gas Dynamics

Radiative Gas Dynamics

- Gas Dynamics
- Physical kinetics
- Chemical Physics

Radiation Heat Transfer

Radiative Model

Optical model:
Absorption coefficients, emission coefficients, scattering coefficients and scattering indicatrix

Cross-sections of the elementary radiative processes

Quantum mechanics and quantum chemistry

Thermodynamics and Statistical Physics

Methods for solving RHT problems
MHD/RGD: Governing equations

\[ \frac{\partial p}{\partial t} + \text{div} \rho \mathbf{V} = 0 \]

\[ p = \frac{R_0}{M} \rho T \]

\[ \frac{\partial \rho \mathbf{V}}{\partial t} + \text{div} \left[ (\rho \mathbf{V}) \cdot \mathbf{V} \right] = -\text{grad} (p) - \frac{1}{\mu_0} [\mathbf{J} \times \mathbf{B}] + \mathbf{F}_\tau + \mathbf{g} \rho + \rho_e \mathbf{E} \]

\[ \frac{\partial}{\partial t} \left( \rho e + \frac{\rho \mathbf{V}^2}{2} + \frac{\mathbf{B}^2}{2 \mu_0} \right) + \text{div} \left[ \rho \mathbf{V} \left( e + \frac{\mathbf{V}^2}{2} + \frac{p}{\rho} + \frac{p_m}{\rho} \right) \right] = \text{div} (\lambda \text{grad} T) + \text{div} \mathbf{W}_{\text{Rad}} + A_\tau + \rho (\mathbf{g} \cdot \mathbf{V}) + (\mathbf{J} \cdot \mathbf{E}) \]

\[ \frac{\partial J_v(s, \Omega, t)}{\partial s} + \left[ \kappa_v(s) + \sigma_v(s) \right] J_v(s, \Omega, t) = \]

\[ = J_{v_{\text{em}}}(s, t) + \frac{1}{4\pi} \sigma_v(s) \int_{\Omega=4\pi} p(s; \Omega', \Omega; \nu) J_{v'}(s, \Omega', t) d\Omega' \]
Laser Plasma Aerodynamics
Objectives of the Laser Plasma Aerodynamics development

- Study of steady-state and unsteady regimes of the Laser Supported Waves (basic physics)
- Laser supported rockets engines (LSRE, lightcrafts)
- Technological applications of laser plasma plumes
- Using laser sparks and LSW for flow control in different aerophysic applications
Physics of the Laser Supported Waves (LSW)

Laser Beam: CW CO2-laser (10.6 micron)  
P~5 kW

Laser Plasma
Laser Beam
Laser Plasma propagation: U=U(W, p, gas, ...)

Laser Beam: CW CO2-laser (10.6 micron)  
P~5 kW

Laser Plasma
Gas Flow  
U~ 1-10 m/s

Laser impulse duration t>1-5 ms

Gas flow
Laser supported plasma
Laser beam
Laser Supported Wave

2 August 2005  
41st Course: Molecular Physics  
and Plasma in Hypersonics
Physics of the Laser Supported Waves (LSW)

- Initiation of the first electrons
- Heating of electrons in the field of laser radiation
- Collisional heating of neutral particles
- Diffusion of electrons
- Avalanche ionization of atoms and molecules
- Thermo-conductive and radiative heating of cold gas
- Gas movement
Physics of the Laser Supported Waves (LSW)

Parameters of the Laser Rocket Engines (LRE) and Laser Supported Plasma Generators (LSPG) are very close to powerful arc plasma generators!
**Approaches**

- Unsteady Navier-Stokes equations for chemically reacting gases
- Radiation heat transfer equation for spectral, group and integral heat radiation
- Real thermophysic, transport and optical properties of gases (air, hydrogen, CO\textsubscript{2}+N\textsubscript{2}, Ar, etc.)
- The temperature region: $T = 300 – 30\,000\,K$
- The pressure region: $p = 0.0001 - 100\,\text{atm}$
Thermophysical properties (Capitelli’s sci. group)

Specific heat at constant pressure

Air, p=1 atm

H₂, p=1 atm
Laser Plasma Aerodynamics

Thermophysical properties (Capitelli’s sci. group)

Air, p=1 atm

Viscosity coefficient, kg/(m*s)

Total thermal conductivity, W/(m*K)

Temperature, K

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Laser Plasma Aerodynamics

**Thermophysical properties (Capitelli’s sci. group)**

$H_2$, $p=1$ atm

![Graph showing thermal conductivity](image1)

![Graph showing viscosity](image2)
Laser Plasma Aerodynamics

Optical properties: spectral models

Air, p=1 atm

Absorption coefficient, 1/cm

T = 6000 K
P = 1.000 atm
Ro = 0.04436 kg/m
N = 0.15787
O = 0.32381
E- = 0.00020
NO = 0.00031
N2 = 0.00830
O2 = 0.00031
O+ = 0.00000
N+ = 0.00000
N2+ = 0.00000
O2+ = 0.00000
NO+ = 0.00020

Absorption coefficient, 1/cm

T = 20000 K
P = 1.000 atm
Ro = 0.00442 kg/m
N = 0.01604
O = 0.00683
E- = 0.49008
NO = 0.00000
N2 = 0.00000
O2 = 0.00000
N+ = 0.38168
O+ = 0.10537
N2+ = 0.00000
O2+ = 0.00000
NO+ = 0.00000
Laser Plasma Aerodynamics

Optical properties: spectral models

$H_2$, $p=1$ atm
Optical properties: group models

Air, p=1 atm
Laser Plasma Aerodynamics

Optical properties: group models

$H_2$, $p=1$ atm
Laser Plasma Aerodynamics

Radiative gas dynamic model of the LSPG (the laminar flow)

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{1}{r} \frac{\partial (r \rho v)}{\partial r} = 0
\]

\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial r} \right) = -\frac{\partial p}{\partial x} + 4 \frac{\partial}{\partial x} \left( \mu \frac{\partial u}{\partial x} \right) +
\]

\[
+ \frac{1}{r} \frac{\partial}{\partial r} \left( r \mu \frac{\partial u}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \mu \frac{\partial v}{\partial x} \right) - \frac{2}{3} \frac{\partial}{\partial x} \left( \mu \frac{\partial v}{\partial r} \right)
\]

\[
\rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial r} \right) = -\frac{\partial p}{\partial r} +
\]

\[
+ \frac{\partial}{\partial x} \left( \mu \frac{\partial u}{\partial r} \right) + \frac{\partial}{\partial x} \left( \mu \frac{\partial v}{\partial x} \right) + \frac{4}{3} \frac{\partial}{\partial r} \left( r \mu \frac{\partial v}{\partial x} \right) - 2 \frac{\mu v}{r^2} -
\]

\[
- \frac{2}{3} \frac{r}{r} \frac{\partial}{\partial r} \left( r \mu \frac{\partial u}{\partial x} \right) - \frac{2}{3} \frac{1}{r} \frac{\partial \mu v}{\partial r} + \frac{2}{3} \mu \left( \frac{\partial u}{\partial x} + \frac{1}{2} \frac{\partial (r v)}{\partial r} \right)
\]
Radiative gas dynamic model of the LSPG (the laminar flow)

\[ \rho c_p \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial r} \right) = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \lambda \frac{\partial T}{\partial r} \right) + Q_\Sigma \]

\[ Q_\Sigma = Q_L - Q_{HR} \]

\[ Q_L = \frac{\mu_\omega P_L}{\pi R_b^2} \exp \left( - \frac{r^2}{R_b^2} \right) \quad \frac{\partial P_L}{\partial x} = -\mu_\omega (x, r = 0) P_L \]

\[ Q_{HR} = \sum_{g=1}^{N_g} \kappa_g (U_{b,g} - U_g) \Delta \omega_g \]

\[ \text{div} \left( \frac{1}{3\kappa_g} \text{grad} U_g \right) = -\kappa_g (U_{b,g} - U_g) \]

\[ g=1,2,\ldots,N_g \]
Radiative gas dynamic model of the LSPG (the turbulent flow)

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{1}{r} \frac{\partial (r \rho v)}{\partial r} = 0,
\]

\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial r} \right) = - \frac{\partial p}{\partial x} + \frac{4}{3} \frac{\partial}{\partial x} \left( \mu_{\text{eff}} \frac{\partial u}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \mu_{\text{eff}} \frac{\partial u}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \mu_{\text{eff}} \frac{\partial v}{\partial r} \right),
\]

\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial r} \right) = - \frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( \mu_{\text{eff}} \frac{\partial u}{\partial r} \right) + \frac{\partial}{\partial x} \left( \mu_{\text{eff}} \frac{\partial v}{\partial x} \right) + 4 \frac{1}{3} \frac{\partial}{\partial r} \left( r \mu_{\text{eff}} \frac{\partial v}{\partial r} \right) - 2 \frac{\mu_{\text{eff}} v}{r^2} - \frac{2}{3} \frac{\partial}{\partial r} \left( r \mu_{\text{eff}} \frac{\partial u}{\partial x} \right) - \frac{2}{3} \frac{\partial}{\partial r} \left( r \mu_{\text{eff}} \frac{\partial u}{\partial r} \right) + \frac{2}{3} \frac{\partial}{\partial r} \left( \frac{\partial u}{\partial x} + \frac{1}{2} \frac{\partial}{\partial r} \right),
\]

\[
\rho c_p \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial r} \right) = \frac{\partial}{\partial x} \left( \lambda_{\text{eff}} \frac{\partial T}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \lambda_{\text{eff}} \frac{\partial T}{\partial r} \right) + Q_\Sigma,
\]
Radiative gas dynamic model of the LSPG (the turbulent flow)

\[ Q_\Sigma = Q_L - Q_{HR}, \quad Q_L = \frac{\mu \omega P}{\pi R_L^2} \exp\left(-\frac{r^2}{R_L^2}\right), \quad \frac{\partial P}{\partial x} = -\mu \omega (x, r = 0)P, \]

\[ Q = \sum_{k=1}^{N_k} \kappa_k (U_{b,k} - U_k) \Delta \omega_k, \quad \text{div}\left(\frac{1}{3\kappa_k} \text{grad} U_k\right) = -\kappa_k (U_{b,k} - U_k), \]

\[ \frac{\partial p}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left[r(p \mu u - \frac{\mu t}{\sigma_k} \frac{\partial k}{\partial r})\right] + \frac{\partial}{\partial x} (p \frac{\mu v}{\sigma_k} - \frac{\mu t}{\sigma_k} \frac{\partial k}{\partial x}) = P - \rho \varepsilon, \]

\[ \frac{\partial \rho \varepsilon}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left[r(\rho \varepsilon u - \frac{\mu t}{\sigma_k} \frac{\partial \varepsilon}{\partial r})\right] + \frac{\partial}{\partial x} (\rho \varepsilon u - \frac{\mu t}{\sigma_k} \frac{\partial \varepsilon}{\partial x}) = (C_1 P - C_2 \rho \varepsilon) \frac{\varepsilon}{k} \]

\[ P = \mu_t \left\{ 2\left[\left(\frac{\partial u}{\partial r}\right)^2 + \left(\frac{\partial v}{\partial r}\right)^2 + \frac{u^2}{r^2}\right] + \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial x}\right)^2 \right\} - \frac{2}{3} \left\{ \rho k + \mu_t \left[\frac{\partial u}{\partial x} + \frac{1}{r} \frac{\partial u}{\partial r}\right] \right\} \]

\[ -\frac{\lambda_t}{\rho^2} \left(\frac{\partial \rho}{\partial r} \frac{\partial \rho}{\partial r} + \frac{\partial \rho}{\partial x} \frac{\partial \rho}{\partial x}\right), \quad \mu_t = C_\mu \rho k^2 / \varepsilon, \quad \lambda_t = \mu_t c_p / Pr_t \]
Temperature distribution inside cylindrical chamber of hydrogen LSPG at $U_o=40$ m/s, $P=100$ kWatt
Laser Supported Plasma Generator

Investigation of the laser plasma flows:

- Prediction of exit plasma flows
- Instabilities of the plasmodynamic configurations
- The instabilities supression
Laser Supported Plasma Generator

Plasma instabilities in LSPG at $U_0=30$ m/s, $P=100$ kWatt

Air

![Graph showing plasma instabilities in LSPG at $U_0=30$ m/s, $P=100$ kWatt]
Laser Supported Plasma Generator

Prediction of Radiative Heating of Internal Surfaces of Hydrogen and Air Laser Supported Plasma Generators
Motivation:

- Plasma temperature achieves $T \sim 20,000$ K
- There is a high-temperature tail of the plasma behind LSW front at presence of internal gas flow.
- Prediction of radiative heating of LSPG internal surfaces.
Hydrogen

Temperature distribution in LSPG at $U_0=20$ m/s, $P=100$ kWatt
Laser Supported Plasma Generator

Hydrogen

Temperature distribution in LSPG at $U_o=30$ m/s, $P=100$ kWatt
Laser Supported Plasma Generator

Hydrogen

Temperature distribution in LSPG at $U_0=50$ m/s, $P=100$ kWatt
Laser Supported Plasma Generator

Hydrogen

Temperature distribution in LSPG at $U_0=60$ m/s, $P=100$ kWatt
Laser Supported Plasma Generator

Hydrogen

Temperature distribution in LSPG at $U_o=70$ m/s, $P=100$ kWatt
Laser Supported Plasma Generator

Air; Laminar flow

Temperature distribution in LSPG at $U_0=30$ m/s, $P=100$ kWatt
Temperature distribution in LSPG at $U_0=30$ m/s, $P=100$ kWatt
Laser Supported Plasma Generator

Discrete Ordinates Method (DOM): Radiation heat flux, W/cm**2

Distribution of integral radiation heat flux along internal cylindrical surface of the LSPG, W/cm², at entrance velocity 30 m/s

Dependence of the radiation heat flux upon on the flow regime (laminar/turbulent)

Air
Laser Supported Plasma Generator

DOM: Radiation heat flux, W/cm**2

Radiation flux distribution along cylindrical surface for different entrance velocities (DOM: S12)

Group Radiation flux distribution, Watt/cm², at x=3 cm on the cylindrical surface

Hydrogen
Laser Plasma Aerodynamics

Laser Supported Waves in Free Space

Laser Beam

Laser Plasma propagation: \( U = U(W, p, \text{gas}, \ldots) \)
Laser Plasma Aerodynamics

Laser Supported Waves in Free Space

Laser Beam: CW CO2-laser (10.6 micron) P~5 kW
Gas Flow U~ 1-10 m/s
Laser Plasma Aerodynamics

Laser Plumes: Laser Impulse Interaction with Material

Laser Beam

Laser Plasma propagation: \( U = u(W, p, \text{gas}, \ldots) \)

Without Magnetic field

With Magnetic field

50ns 80ns 110ns 140ns 200ns

5mm
Laser Plasma Aerodynamics

Laser Plumes: Schematic of the problem and numerical simulation
Laser Plasma Aerodynamics

Laser Plumes: Schematic of the problem and numerical simulation
Laser Plasma Aerodynamics

Laser Supported Waves as the Late Stage of Laser Impulse/Material Interaction

Laser Beam

Laser Plasma propagation: \( U = U(W, p, \text{gas}, ...) \)
Laser Plasma Aerodynamics

\[ R_{\text{Laser beam}} = 0.1 \text{ cm, } P = 15 \text{ kW} \]
Laser Plasma Aerodynamics

\( R_{\text{Laser beam}} = 0.5 \text{ cm}, \ P = 25 \text{ kW} \)
Laser Plasma Aerodynamics

\( R_{\text{Laser beam}} = 0.5 \text{ cm}, \ P = 25 \text{ kW} \)
Laser Plasma Aerodynamics

\[ R_{\text{Laser beam}} = 1.0 \text{ cm}, \ P = 60 \text{ kW} \]
Laser Plasma Aerodynamics

$R_{\text{Laser beam}} = 1.0 \text{ cm}$, $P = 60 \text{ kW}$
3D MHD of Plume of the Hall Plasma Thrusters at Ionospheric Conditions
Problem statement

- Prediction of plasmodynamic and electro-dynamic characteristics of the Hall Plasma Thruster (HPT) or Pulsed Plasma Thruster (PPT) plumes
- Analysis of the possibility to use MGD codes (ideal and non-ideal) for describing interaction of the HPT/PPT plasma plumes with partially ionized rarefied atmosphere
- Creation 3D MGD/CFD codes as alternative for PIC/DSMC codes
The governing equations

\[ \frac{\partial \mathbf{U}}{\partial t} + \nabla \cdot \mathbf{F}_\Sigma = Q \]

\[ \frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}}{\partial \mathbf{x}} + \frac{\partial \mathbf{g}}{\partial \mathbf{y}} + \frac{\partial \mathbf{h}}{\partial \mathbf{z}} = Q \]

\[ \mathbf{F}_\Sigma = \mathbf{F}^{\text{Eu}} + \mathbf{F}^{\text{NS}} + \mathbf{F}^{\text{MGD}} + \mathbf{F}^{\text{VMGD}} \]

\[ \mathbf{F}_\Sigma = i\mathbf{f} + j\mathbf{g} + k\mathbf{h} \]

\[ \mathbf{f} = f^{\text{Eu}} + f^{\text{NS}} + f^{\text{MGD}} + f^{\text{VMGD}} \]

\[ \mathbf{g} = g^{\text{Eu}} + g^{\text{NS}} + g^{\text{MGD}} + g^{\text{VMGD}} \]

\[ \mathbf{h} = h^{\text{Eu}} + h^{\text{NS}} + h^{\text{MGD}} + h^{\text{VMGD}} \]
Initial conditions

\[ \rho_* = 2.0 \cdot 10^{-9} \text{ kg/m}^3, \quad p_* = 4.49 \cdot 10^{-4} \text{ Pa} \]

\[ B_0 = 5 \cdot 10^{-5} \text{ T}, \quad \alpha_{B,Y} = 30^0 \]

\[ W_{\text{inf}} = -6.0 \text{ km/s}, \quad \vartheta_{\text{inf}} = 30^0 \]

\[ W_{\text{plume}} = -25 \text{ km/s}, \quad \rho_{\text{plume}} = 2.0 \cdot 10^{-7} \text{ kg/m}^3, \]
\[ p_{\text{plume}} = 20 \text{ Pa}, \quad R_{\text{exit}} = 0.03 \text{ m} \]

\[ T_{\text{HPT}} = 6 \mu s, \quad T_{\text{simulation}} = 70 \mu s \]
3D plasma plume: Numerical simulation results: $t=3 \, \mu s$
3D plasma plume: Numerical simulation results: t=10 μs
3D plasma plume: Numerical simulation results: $t=20 \, \mu s$
3D plasma plume: Numerical simulation results: $t=30\ \mu s$
3D plasma plume: Numerical simulation results: $t=40 \, \mu s$
3D plasma plume: Numerical simulation results: t=50 μs
3D plasma plume: Numerical simulation results: t=60 µs
3D plasma plume: Numerical simulation results: t=3 μs
3D plasma plume: Numerical simulation results: $t=20 \mu s$
3D plasma plume: Numerical simulation results: $t=40 \, \mu s$
3D plasma plume: Numerical simulation results: $t=60 \, \mu s$
3D Plasma plumes: Conclusions

- At distances ~0.5 m from HPT its plasma plume begins to interact with ambient ionospheric flow and frozen magnetic field.
- High efficiency of the 3D code based on the splitting method is illustrated: Calculation time < 1.0 hour (Pentium-IV, f=3.2 GHz, mesh 100x100x100)
Safety rescue systems for astronauts and payload
Safety rescue systems for astronauts and payload

Numerical simulation of fireballs generated at probable explosions: ARIANE-V, Zenith, Proton, Aurora

Fireball generated at Challenger catastrophe, January 1986
Safety rescue systems for astronauts and payload

Shock-wave structure at ARIANE-V explosion at altitude 55 km and at flight velocity $V=2\text{ km/s}$
Safety rescue systems for astronauts and payload

- PROTON
- Radiative Fireball above launch pad
- Fireball dynamics **without** RHT
Safety rescue systems for astronauts and payload

- PROTON
- Radiative Fireball above launch pad
- Fireball: full RGD model
Safety rescue systems for astronauts and payload

- PROTON
- Radiative Fireball above launch pad
- Fireball: **volume emission model** (no reabsorption)
Numerical simulations of aerospace RGD applications

Non-equilibrium radiation of shock waves for entry and re-entry velocities
Motivation

• Creation of closed hierarchy theory of non-equilibrium kinetic processes behind shock waves

• Prediction of real shock waves (air, CO$_2$-N$_2$) at velocities $V=3$-$12$ km/s and pressures $\sim 0.1$-$1000$ torr

• Comparison of numerical simulations (spectral radiation emissivity !) with experimental data and calculations of other authors
Physical-chemical processes included in the developed model

• Chemical reactions (thermal dissociation, neutral exchange reactions)
• Reactions involving charged particles (dissociative recombination reactions, associative ionization, electron-impact ionization, charge-exchange reactions, ion-molecule reactions)
• Excitation of CO$_2$, N$_2$, CO vibration modes during translational-vibrational (VT), and vibrational-vibrational (VV) energy exchange
• Nonequilibrium dissociation
• Nonequilibrium radiation
Gas dynamic model:

\[ \rho u = \rho_0 u_0, \quad p + \rho u^2 = p_0 + \rho_0 u_0^2, \quad h + \frac{u^2}{2} = h_0 + \frac{u_0^2}{2}, \]

where:

\[ p = \frac{\rho R_0 T}{M_\Sigma} = n k T, \quad M_\Sigma = \sum_{i=1}^N \mu_i x_i, \quad \mu_i = m_i N_A, \]

\[ h = C_p T + \frac{R_0}{M_\Sigma} \sum_{i}^{L_2+L_3} x_i \sum_{j=1}^{N_{V,i}} q_{i,j} \frac{\theta_{i,j}}{\exp\left(\frac{\theta_{i,j}}{T}\right) - 1}, \]

\[ C_p = \left( \frac{5}{2} + \sum_{l=1}^{L_2} x_l + \frac{3}{2} \sum_{i=1}^{L_3} x_i \right) \frac{R_0}{M_\Sigma} \]
Model of chemical kinetics

\[ \sum_{i=1}^{N} a_{i,j} [X_i]^j \rightleftharpoons \sum_{i=1}^{N} b_{i,j} [X_i] \]

\[ \frac{dX_k}{dt} = \sum_{j=1}^{N_R} \left[ (b_{k,j} - a_{k,j}) k_j^f \prod_{i=1}^{N} X_i^{a_{ij}} + (a_{k,j} - b_{k,j}) k_j^r \prod_{i=1}^{N} X_i^{b_{ij}} \right], \quad k = 1, 2, \ldots, N \]

\[ k^\pm_j = A^\pm T^{n^\pm} \exp \left[ -\frac{E^\pm}{kT} \right] \]

\[ \log K_j = A_{eq,j} + B_{eq,j} \frac{1000}{T}, \quad K_j = \frac{\prod \tilde{p}_{l,j}^{n_{i,j}}}{\tilde{p}_{e,j} \tilde{p}_{j}} \]
Model of vibrational kinetics

\[
\frac{de_m}{dt} = Q_{vT}^m + Q_{vv}^m + Q_{cv}^m,
\]

\[
Q_{vT}^m = \frac{e_0^m - e_m}{\tau_m}, \quad \tau_m = \left( \sum_{i=1}^{N} \frac{x_i}{\tau_{m,i}} \right)^{-1}, \quad Q_{vv}^m = \sum_n k_{m,n} F_{m,n},
\]

\[
F_{m,n} = \frac{r}{g_m} \left[ e_n^q \left( e_m + 1 \right)^r \exp \left( \frac{q\theta_n}{T} - \frac{r\theta_m}{T} \right) - e_m^r \left( e_n + 1 \right)^q \right],
\]

\[
k_{m,n} = \sum_l x_l (k_{m,n})_l, \quad Q_{cv}^m = \frac{1}{X_i} \sum_{j=1}^{N_r} (e_{mj} - e_m) \left( \frac{dX_m}{dt} \right)_j,
\]

\[
e_m = \frac{1}{\exp \left( \frac{\theta_m}{T_{v,m}} \right) - 1}
\]
Model of vibrational kinetics

\[ \tau = \tau_{VT} + \frac{1}{N_{i} \sigma_{v} \sqrt{8kT/(\pi M_{m})}}, \sigma_{v} = \sigma_{v}' (50000/T)^{2} \]

\[ p \tau_{VT} = \exp[A_{VT} (T^{-1/3} - B_{VT}) - 18.42] \]

\[ k_{m,n}^{-1} = \tau_{VV}, p \tau_{VV} = \exp\left(A_{VV} + B_{VV} \frac{1}{T^{1/3}} + C_{VV} \frac{1}{T^{2/3}} + D_{VV} T^{1/3}\right) \]
Model of vibrational kinetics

\[ e_{mj} = \frac{1}{\exp\left(\frac{\theta_m}{T_F}\right) - 1} - \frac{D_m / \theta_m}{\exp\left(\frac{D_m}{T_F}\right) - 1} \]

\[ T_F = \frac{1}{T_{m,n}} - \frac{1}{T} - \frac{1}{U}, \quad U = 3T \]

\[ k(T_v, T) = k^0(T)Z(T_v, T) \]

\[ Z(T, T_v) = \frac{Q(T)Q(T_F)}{Q(T_v)Q(-U)}, \quad Q(T_\alpha) = \frac{1 - \exp\left(-D_0 / T_\alpha\right)}{1 - \exp\left(-\theta / T_\alpha\right)} \]

\[ T_\alpha = \{T, \ T_v, \ T_F, \ -U\}; \quad T_v < T \]
The electronic energy conservation model:

\[ Q_{ei} = 1.21 \times 10^{20} X_e X_i \frac{T - T_e}{T_e^{3/2}} \ln \Lambda \]

\[ Q_{ea} = 3.378 \times 10^{10} X_e X_a \sqrt{T_e (T - T_e)} \left[ 1 - \left( 1 + \frac{T_e}{T_a} \right)^{-1} \right] \]

\[ Q_{ai} = T \sum_{q=1} \alpha_q k_q^f X_a X_{a_q} - T_e \sum_{q=1} \beta_q k_q^r X_e X_{(a_q b_q)}^+ \]

\[ Q_{ion} = \gamma T_k^{f \gamma} N_e X_N X_e - \delta T_k^{f \delta} O_e X_O X_e - \theta T_k^{f \theta} C_e X_C X_e \]

\[ Q_{ev} = 2 \times 10^{-16} \sum_V n_e n_\nu \omega_{e,\nu} P_{1,0,\nu} \cdot \left[ \frac{1}{1 - \exp \left( -\frac{1.44 \omega_{e,\nu}}{T_e} \right)} \right]^2 - \left[ \frac{1}{1 - \exp \left( -\frac{1.44 \omega_{e,\nu}}{T_\nu} \right)} \right]^2 \]
Model of spectral radiation emissivity

\[
j_{\lambda} = 3.202 \cdot 10^{-10} \frac{N_{eel}}{Q_{vr} \lambda^6} \sum_{v'} \sum_{v''} \frac{S_{v'v''}}{|\Delta B_v|} \exp \left[ -\frac{hc}{kT_v} E_{eel}(v') \right] \cdot \exp \left[ -\frac{hc}{kT_r} \frac{B_v}{\Delta B_v} (\omega - \omega_{v'v''} + B_{v'}) \right], \text{W/(cm}^3 \cdot \mu\text{m} \cdot \text{sr)}
\]
Prediction of Nonequilibrium Radiation From CO$_2$-N$_2$ and Air Shock Waves

Validation of the model

• Comparative analysis of calculated spectral radiation intensities with experimental data and theoretical predictions of other authors

  – the Kozlov-Losev-Ponomarenko experiments, Moscow State University, 1998-1999
Non-equilibrium radiation behind the shock wave for the Thomas-Menard experiments: $p_0=0.25$ torr and $U_s=7620$ m/s (9%CO$_2$-90%N$_2$-1%Ar).

The Boltzmann distribution of excited electronic levels is presumed.

Non-equilibrium radiation behind the shock wave for the Thomas-Menard experiments: $p_0=0.25$ torr and $U_s=7620$ m/s (9%CO$_2$-90%N$_2$-1%Ar). The radiative-collisional model for excited electronic levels is presumed. Comparison of the calculations (solid line) with the experimental data (diamonds)
Non-equilibrium radiation behind the shock wave for the Thomas-Menard experiments: $p_0=0.25$ torr and $U_s=7620$ m/s (30%CO$_2$-70%N$_2$). The radiative-collisional model for excited electronic levels is presumed. Comparison of the calculations (solid line) with the experimental data (diamonds)
Prediction of Nonequilibrium Radiation From CO₂-N₂ and Air Shock Waves

Temperature distributions behind the shock wave for the Thomas-Menard experiments: \( p₀ = 0.25 \) torr and \( Uₙ = 7620 \) m/s (30%CO₂-70%N₂). The radiative-collisional model for excited electronic levels is presumed.
Non-equilibrium radiation behind the shock wave for conditions of the Kozlov-Losev-Romanenko experiments:

\( p_0 = 0.5 \text{ torr and } U_s = 3750 \text{ m/s (4.8}\%\text{CO}_2-0.15\%\text{N}_2-95.05\%\text{Ar}). \)

The Boltzmann distribution of excited electronic levels is presumed. The radiative-collisional model for excited electronic levels is presumed.
Resume (CO$_2$+N$_2$):

1. Two models of excitation of the electronic energy levels of diatomic molecules have been studied for conditions of the Thomas-Menard experiments, the Kozlov-Losev_Ponomarenko experiments, and for the Park-Howe-Jaffe-Candler calculations. The first model presumes the Boltzmann distribution of the excited levels, and the second one demands integration of equations of the radiative-collisional kinetic model.

2. Comparison of the present calculations with experimental and theoretical data permits to make a conclusion about acceptability of the model for prediction of the non-equilibrium radiation for spacecraft entering the Martian atmosphere at velocities between 3÷8 km/s. However, there is a need to develop and validate such theoretical models in comparisons with new experimental data.
Prediction of Nonequilibrium Radiation From CO$_2$-N$_2$ and Air Shock Waves

Air:

V=12 km/s

H=70 km
Prediction of Nonequilibrium Radiation From CO$_2$-N$_2$ and Air Shock Waves

Air:

V=12 km/s
H=70 km

Heating of the electronic gas

Temperatures

2 August 2005 41st Course: Molecular Physics and Plasma in Hypersonics
Prediction of Nonequilibrium Radiation From CO$_2$-N$_2$ and Air Shock Waves

Air:
V = 12 km/s
H = 70 km

Energy Losses

- $T_0 = 0.217 \times 10^3$
- $P_0 = 0.520 \times 10^2$
- $U_0 = 0.120 \times 10^7$
- $R_{00} = 0.839 \times 10^{-7}$
- $H_0 = 0.217 \times 10^{10}$
- $\text{TEMPE} = 0.217 \times 10^3$
- $\text{Plaser} = 0.100 \times 10^1$

- $T_1 = 0.703 \times 10^5$
- $P_1 = 0.101 \times 10^6$
- $U_1 = 0.201 \times 10^6$
- $R_{01} = 0.502 \times 10^{-6}$
- $H_1 = 0.702 \times 10^{12}$
Resume (air)

All test data and preliminary calculations show that the local thermodynamic equilibrium (LTE) is not realized in spatial zone (~3 cm) behind shock wave at shock wave velocity more than 9 km/s and $P_1=0.05-0.2$ torr.

This effect should be studied and taken into account at determination of the ionization and radiation characteristics of super-orbital shock layer.
Numerical simulations of aerospace RGD applications

Entry and Re-Entry Hypersonics
Radiative Gas Dynamics

Gas Dynamics

Physical kinetics

Chemical Physics

Radiation Heat Transfer

Radiative Model

Optical model:
Absorption coefficients, emission coefficients, scattering coefficients and scattering indicatrix

Cross-sections of the elementary radiative processes

Quantum mechanics and quantum chemistry

Radiation Transfer Model

Methods for solving RHT problems

Thermodynamics and Statistical Physics
Entry and Re-Entry Hypersonics

General objective:
Verification of gasdynamic, kinetic, radiative models for space vehicle aerothermodynamics prediction

Model of Mars Sampler Return Orbiter (MSRO), postulated as the base model for TC3
Entry and Re-Entry Hypersonics

TC3: MSRO Trajectory parameters

<table>
<thead>
<tr>
<th>No.</th>
<th>Time, s</th>
<th>Density, g/cm³</th>
<th>Pressure, erg/cm³</th>
<th>Velocity, m/s</th>
<th>Temperature, K</th>
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<td>140</td>
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<td>140</td>
</tr>
<tr>
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<td>$3.07 \cdot 10^{-7}$</td>
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<td>3998</td>
<td>140</td>
</tr>
<tr>
<td>4</td>
<td>270</td>
<td>$2.82 \cdot 10^{-7}$</td>
<td>7.6</td>
<td>3536</td>
<td>140</td>
</tr>
</tbody>
</table>
### Governing equations

\[
\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{E}}{\partial x} + \frac{\partial \mathbf{F}}{\partial y} = \mathbf{G}
\]

\[
\mathbf{U} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho e \\ \rho_1 \\ \rho_2 \\ \vdots \\ \rho_N \end{bmatrix}, \quad \mathbf{E} = \begin{bmatrix} \rho u \\ \rho uu + p + \tau_{xx} \\ \rho v + \tau_{xy} \\ \rho u(e + \frac{p}{\rho}) + q_x \\ \rho_1 u + J_{1,x} \\ \rho_2 u + J_{2,x} \\ \vdots \\ \rho_N u + J_{N,x} \end{bmatrix}, \quad \mathbf{F} = \begin{bmatrix} \rho v \\ \rho vu + \tau_{yx} \\ \rho vv + p + \tau_{yy} \\ \rho v(e + \frac{p}{\rho}) + q_y \\ \rho_1 v + J_{1,y} \\ \rho_2 v + J_{2,y} \\ \vdots \\ \rho_N v + J_{N,y} \end{bmatrix}, \quad \mathbf{G} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ Q_{\Sigma} \\ \sigma_1 \\ \sigma_2 \\ \vdots \\ \sigma_N \end{bmatrix}
\]

\[
Q_{\Sigma} = \Phi + Q_{\text{Rad}} - p \text{div} \mathbf{V} + Q_{\alpha}
\]

\[
q = -\lambda \text{grad} T + \sum_{i=1}^{N} h_i J_i
\]

\[
J_i = -D_i \text{grad} \rho_i, \quad i = 1, 2, \ldots, N
\]
Entry and Re-Entry Hypersonics

Governing equations

\[ h_i = \int_{T_0}^{T_i} c_{p,i} dT + h_{i,0} \]
\[ e_i = \int_{T_0}^{T_i} c_{v,i} dT + e_{i,0} \]
\[ e = h - \frac{p}{\rho} = \sum_{i}^{N} h_i Y_i - \frac{p}{\rho} \]

\[ \Phi = \mu \left\{ 2 \left[ \left( \frac{\partial v}{\partial r} \right)^2 + \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{v}{r} \right)^2 \right] + \left( \frac{\partial u}{\partial r} + \frac{\partial v}{\partial x} \right)^2 - \frac{2}{3} \left( \text{div} \mathbf{V} \right)^2 \right\} \]

\[ \tau_{xx} = 2 \mu \frac{\partial u}{\partial x} - \frac{2}{3} \mu \text{div} \mathbf{V} \]
\[ \tau_{yy} = 2 \mu \frac{\partial v}{\partial y} - \frac{2}{3} \mu \text{div} \mathbf{V} \]
\[ \tau_{xy} = \mu \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \]

\[ \sigma_i = M_i \sum_l (\nu_{i,l}'' - \nu_{i,l}') \left( k_{f,j} \prod_{j=1}^{N} [X_j]^{\nu_{j,i}} - k_{r,j} \prod_{j=1}^{N} [X_j]^{\nu_{j,i}} \right) \]
\[ [X_j] = Y_j \frac{\rho}{M_j} \]
\[ Y_i = \frac{\rho_i}{\rho} \]

\[ Q_{Rad} = \text{div} \mathbf{W}_{Rad} \]
Entry and Re-Entry Hypersonics

Governing equations:
Energy conservation equation

\[ \rho c_p \frac{\partial T}{\partial t} + \rho c_p \mathbf{V} \nabla T = \text{div} \left( \lambda \nabla T \right) + \frac{\partial p}{\partial t} + \mathbf{V} \nabla p + \]
\[ + \Phi_\mu + Q_{\text{vib}} + \sum_{i=1}^{N_s} \rho c_{p,i} D_i \left( \nabla Y_i \cdot \nabla T \right) - \text{div} \mathbf{q}_R - \sum_{i=1}^{N_s} h_i \dot{\omega}_i \]

\[ \Phi_\mu = \mu \left[ 2 \left( \frac{v}{r} \right)^2 + 2 \left( \frac{\partial v}{\partial r} \right)^2 + 2 \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial r} \right)^2 - \frac{2}{3} \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial r} + \frac{v}{r} \right)^2 \right] \]
Entry and Re-Entry Hypersonics

Governing equations

\[
\frac{\partial \rho_i}{\partial t} + \text{div} \rho_i \mathbf{V} = -\text{div} \mathbf{J}_i + \mathbf{\omega}_i, \quad i = 1, 2, \ldots, N_s
\]

\[
\frac{\partial \rho e_{v,m}}{\partial t} + \text{div} \left( \rho \mathbf{V} e_{v,m} \right) = \dot{e}_{v,m}, \quad m = 1, 2, \ldots, N_v
\]

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

\[
\dot{e}_{v,m} = \rho_i(m) \frac{e^0_{v,m} - e_{v,m}}{\tau_m} - e_{v,m} \dot{w}_i(m)
\]

\[
e_{v,m} = \frac{R_0 \theta_m \rho_i(m)}{M_i(m) \left[ \exp \left( \frac{\theta_m}{T_{V,m}} \right) - 1 \right]}
\]

\[
q_R = q_R (z) = \int d\Omega \int_{\Delta \omega_{tot}} J_\omega (\mathbf{r}, \Omega) \Omega d\Omega
\]
Entry and Re-Entry Hypersonics

Governing equations

\[ \sum_{j=1}^{N_s} a_{j,n} \left[ X_j \right] = \sum_{j=1}^{N_s} b_{j,n} \left[ X_j \right], \quad n = 1, 2, \ldots, N_r, \]

\[ W_j = \left( \frac{dX_j}{dt} \right)_n = k_{f,n} \left( b_{j,n} - a_{j,n} \right) \prod_{i=1}^{N_c} X_j^{a_{i,n}} - \]

\[ -k_{r,n} \left( a_{j,n} - b_{j,n} \right) \prod_{i=1}^{N_c} X_i^{b_{i,n}} = S_{f,j} - S_{r,j} \]

\[ k_{f(r),n} = A_{f(r),n} T^{n_{f(r),n}} \exp \left( - \frac{E_{f(r),n}}{kT} \right) \]

\[ K_n = \frac{k_{f,n}}{k_{r,n}} \]
Entry and Re-Entry Hypersonics

Numerical simulation methods

- Time relaxation method
- Flux-corrected methods for the Navier-Stokes equations
- Implicit method with using SOR on lines for mass conservation equations (for chemical species)
- Implicit method with using SOR on lines for energy conservation equation
- $P_1$-approximation of the spherical harmonics method (SHM) for radiation heat transfer equation
- Discreet Ordination Methods for radiation heat transfer equation
- Ray-tracing method was used for prediction of radiation heating of MSRO surface
- Monte-Carlo method was used for calculation of spectral signature of MSRO
Validation of the RGD/CFD Model

Reduced model of Pathfinder studied in experiments, and numerically predicted flowfield.

Validation of the RGD/CFD Model


Measured and numerically predicted (solid line) convective heat flux
Validation of the RGD/CFD Model

Pathfinder:
$t=66 \text{ s}$
Numerically predicted flowfield
Validation of the RGD/CFD Model

Comparison of numerical results on convective heat fluxes along the Mars Pathfinder forebody at $t = 66$ s


Initial grid: MSRO
Entry and Re-Entry Hypersonics

Intermediate grid:
MSRO

r, cm

z, cm

0 100 200 300 400 500 600 700 800 900 1000

2 August 2005

41st Course: Molecular Physics
and Plasma in Hypersonics
Entry and Re-Entry Hypersonics

Final grid: MSRO
Numerical simulation results: MSRO, Point No.1

Temperature distribution. Trajectory point No.1.
Pseudo-catalytic surface

Pressure distribution. Trajectory point No.1.
Pseudo-catalytic surface
Numerical simulation results: MSRO, Point No.2

Temperature distribution. Trajectory point No.2.
Pseudo-catalytic surface

Pressure distribution. Trajectory point No.2.
Pseudo-catalytic surface
Numerical simulation results: MSRO, Point No.3

Temperature distribution. Trajectory point No.3. Pseudo-catalytic surface

Pressure distribution. Trajectory point No.3. Pseudo-catalytic surface
Numerical simulation results: MSRO, Point No.4

Temperature distribution. Trajectory point No.4.
Pseudo-catalytic surface

Pressure distribution. Trajectory point No.4.
Pseudo-catalytic surface
Entry and Re-Entry Hypersonics

Mass fraction of species
Numerical simulation results: MSRO, Point No.1, CO$_2$ mass fraction

Mass fraction of CO$_2$. Trajectory point No.1. Non-catalytic surface

Mass fraction of CO$_2$. Trajectory point No.1. Pseudo-catalytic surface
Numerical simulation results: MSRO, Point **No.2**, CO$_2$ mass fraction

**Mass fraction of CO$_2$. Trajectory point No.2.**
Non-catalytic surface

**Mass fraction of CO$_2$. Trajectory point No.2.**
Pseudo-catalytic surface
Numerical simulation results: MSRO, Point No.3, CO$_2$ mass fraction

Mass fraction of CO$_2$. Trajectory point No.3. Non-catalytic surface

Mass fraction of CO$_2$. Trajectory point No.3. Pseudo-catalytic surface
Numerical simulation results: MSRO, Point No.4, CO₂ mass fraction

Mass fraction of CO₂. Trajectory point No.4.
Non-catalytic surface

Mass fraction of CO₂. Trajectory point No.4.
Pseudo-catalytic surface
Entry and Re-Entry Hypersonics

Numerical simulation results: **convective heating**

Convective heat flux along the MSRO surface for the 2nd trajectory point (non-catalytic surface); the first mixture

Convective heat flux along the MSRO surface for the 2nd trajectory point (pseudo-catalytic surface); the first mixture
Numerical simulation results: radiative heating

Total radiation flux on the MSRO surface. Trajectory point No.1-4. Non-catalytic (left) and pseudo-catalytic (right) surface. 
\( N_g = 91, N_m = 100, N_\theta = 91, N_\phi = 100 \)
Numerical simulation results: MSRO Group radiation fluxes

Spectral radiation fluxes at some points of the MSRO surface.
Trajectory point No.1. Pseudo-catalytic surface.
$N_g = 91, N_m = 100$

Spectral radiation fluxes at some point on the MSRO surface.
Trajectory point No.2. Pseudo-catalytic surface. $N_g = 91, N_m = 100$

Pseudo-catalytic surface
Entry and Re-Entry Hypersonics

Numerical simulation results: MSRO Group radiation fluxes

Spectral radiation fluxes at some points of the MSRO surface.
Trajectory point No.3. Pseudo-catalytic surface.
$N_g=91, N_m=100$

Spectral radiation fluxes at some point on the MSRO surface.
Trajectory point No.4. Pseudo-catalytic surface. $N_g=91, N_m=100$

Pseudo-catalytic surface
Entry and Re-Entry Hypersonics

• Numerical simulation results on radiative heating of a surface of space vehicle MSRO at four trajectory points for opposite assumptions concerning surface catalicity are presented.
• It is shown that radiation heat flux to back surface of entering space vehicle MSRO reaches value of ~ 1 W/cm².
• The radiation fluxes are formed generally by emissivity of CO₂ and CO molecules.
Entry and Re-Entry Hypersonics

Aerothermodynamics of re-entry space vehicle
H=59 km, V=10.6 km/s
Line-by-line calculation of radiating heating:
\[ H = 59 \text{ km}, \quad V = 10.6 \text{ km/s} \]

\[ \uparrow \quad 500 \text{ 000 spectral points} \]
**Entry and Re-Entry Hypersonics**

**CFD-MODEL VERIFICATION BY DATA OF FLIGHT EXPERIMENT FIRE –II**

**FIRE II trajectory conditions**

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Altitude (km)</th>
<th>Velocity (km/s)</th>
<th>Density (kg/m$^3$)</th>
<th>$T_\infty$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1634</td>
<td>76.42</td>
<td>11.36</td>
<td>3.72 $10^{-5}$</td>
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<tr>
<td>1637.5</td>
<td>67.05</td>
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<td>1.47 $10^{-4}$</td>
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<tr>
<td>1640.5</td>
<td>59.26</td>
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<tr>
<td>1643.</td>
<td>53.04</td>
<td>10.48</td>
<td>7.8 $10^{-4}$</td>
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<tr>
<td>1645</td>
<td>48.37</td>
<td>9.83</td>
<td>1.32 $10^{-3}$</td>
<td>285</td>
</tr>
</tbody>
</table>
CFD-MODEL VERIFICATION BY DATA OF FLIGHT EXPERIMENT FIRE –II

The boundary of LTE disturbance on ionization for flight conditions (H-V coordinates).

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Altitude (km)</th>
<th>Velocity (km/s)</th>
<th>Density (kg/m³)</th>
<th>T_∞ (K)</th>
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<tr>
<td>1634</td>
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</tr>
</tbody>
</table>
Entry and Re-Entry Hypersonics

CFD-MODEL VERIFICATION BY DATA OF FLIGHT EXPERIMENT FIRE –II

Spectral absorption coefficient (with atomic lines) in the point of maximal temperature (1), and near to surface (2)
CFD-MODEL VERIFICATION BY DATA OF FLIGHT EXPERIMENT FIRE –II

Spectral radiation flux (with radiation of atomic lines) incident upon the streamlined surface
On-going efforts

- Development of numerical simulation methods for radiation heat transfer problems for 3D curvilinear geometry
- Development of quantum-mechanics and quasi-classical models for prediction of radiative properties of hot gases in non-equilibrium conditions
- Development of quantum-mechanics models for calculation parameters of atomic lines
- Development of RGDSV-2 model for prediction of radiative and convective heating of space vehicles at different assumptions concerning catalytic and ablative properties of SV heat protection material
- Further verification of all calculation data (TC1, TC2, TC3, TC4)
Acknowledgments

The author thanks my friends and colleagues M. Capitelli and D. Giordano for invitation to take part in the lecture course and for many useful discussions.
Radiative Gas Dynamics

Part I
Theoretical basis and general definitions

Part II
Numerical simulations of aerospace RGD applications