Software package to calculate the aerodynamic characteristics of aircrafts

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The Goal of investigation

The goal of this work is to demonstrate developed mathematical model of the flow, numerical algorithm and a software package in order to estimate the influence exerted on the aircraft characteristics by user-specified input parameters.

The investigations were carried out using a specially developed mathematical model and created three-dimensional hydrodynamic code, designed to simulate two components turbulent compressed gas flows around the aircraft.

The Complexity of the Problem

- The flow is essentially three-dimensional and turbulent and, in the general case, can be of mixed type (sub- and supersonic).
- The computational domain has to be large, which is required for the flow characteristics near the air-craft to be reliably determined.
- Relatively narrow boundary layers developing on the aircraft surface have to be resolved.
- The moving medium is multicomponent. In the general case, this is a mixture of fuel combustion products and the ambient air flowing past the aircraft.

Mathematical Models of the Code

- The three-dimensional unsteady Reynolds-averaged compressible Navier-Stokes equations, closed with a model of eddy viscosity and thermal conductivity (RANS model).
- The equations for determining the turbulent flow parameters that allow to calculate turbulent exchange coefficients.
- The equation for determining the concentration of combustion products in a mixture of air--combustion of hydrocarbon fuel.
- Boundary conditions for all functions that define the time and spatial characteristics of gas flow.

Basic Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \qquad \frac{\partial \rho u_i}{\partial t} + \nabla \cdot (\rho u_i \boldsymbol{u}) + \frac{\partial p}{\partial x_i} = \sum_{j=1}^{3} \frac{\partial \tau_{ij}}{\partial x_j}$$

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\rho H \boldsymbol{u}) = \sum_{i,j=1}^{3} \frac{\partial u_j \tau_{ji}}{\partial x_i} + \nabla \cdot (k_\Sigma \nabla T)$$

$$\tau_{ij} = -2\mu_\Sigma \nabla \cdot \boldsymbol{u} + \mu_\Sigma \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

$$E = \int_{T_0}^{T} C_V(T')\,dT' + e_0 + \frac{1}{2}\sum_{i=1}^{3} u_i^2 , \qquad H = \int_{T_0}^{T} C_P(T')\,dT' + h_0 + \frac{1}{2}\sum_{i=1}^{3} u_i^2$$

μ_Σ и k_Σ – effective viscosity and heat conductivity coefficients

C_V и C_P – heat capacity at constant volume and pressure

e_0 и h_0 – energy and specific enthalpy of medium at temperature T_0

State Equation
(смесь совершенных газов)

$$p = R_0 \rho T \left(\frac{1-\beta}{\nu_1} + \frac{\beta}{\nu_2} \right)$$

$$C_P = (1-\beta) C_{P1} + \beta C_{P2}$$

$$C_P = (1-\beta) C_{P1} + \beta C_{P2}$$

$$k_\Sigma = C_P \left(\frac{\mu}{\boldsymbol{Pr}} + \frac{\mu_T}{\boldsymbol{Pr}_T} \right)$$

R_0 – the universal gas constant

ν_i, C_{Pi} – molar masses and heat capacities of the combustion gases

β – mass fraction of the combustion products in the mixture

μ, μ_T – the molecular and eddy viscosities of the mixture

$\boldsymbol{Pr}$, $\boldsymbol{Pr}_T$ – laminar and turbulent Prandtl numbers

Two parameters turbulent Coacley’s q–ω model

$$\frac{\partial \rho q}{\partial t} + \nabla \cdot (\rho q \boldsymbol{u}) = \nabla \cdot \left(\mu_{\Sigma q} \nabla q\right) + \frac{\rho q}{2\omega}\left(C_{\mu} f\, D - \frac{2}{3}\omega \nabla \cdot \boldsymbol{u} - \omega^{2}\right)$$

$$\frac{\partial \rho \omega}{\partial t} + \nabla \cdot (\rho \omega \boldsymbol{u}) = \nabla \cdot \left(\mu_{\Sigma\omega} \nabla \omega\right) + \rho\left[C_{1}\left(C_{\mu} D - \frac{2}{3}\omega \nabla \cdot \boldsymbol{u}\right) - C_{2}\omega^{2}\right]$$

$$D = \sum_{i,j=1}^{3}\left(\frac{\partial u_{i}}{\partial x_{j}} + \frac{\partial u_{j}}{\partial x_{i}}\right)^{2} - \frac{2}{3}(\nabla \cdot \boldsymbol{u})^{2},$$

q – «pseudovelocity

ω – «pseudovorticity

$$\mu_{\Sigma\omega} = \mu + 1.3\mu_{T}, \qquad \mu_{\Sigma q} = \mu + \mu_{T},$$

$$\mu_{T} = C_{\mu} f(n) \rho \frac{q^{2}}{\omega}, \quad f(n) = 1 - exp\left(-0{,}0065 \frac{\rho q n}{\mu}\right),$$

$$C_{1} = 0{,}045 + 0{,}405 f(n), \quad C_{2} = 0{,}92, \quad C_{\mu} = 0{,}09$$

Substance Mixing model

$$\frac{\partial C_a}{\partial t} + \frac{\partial}{\partial x}\left(uC_a - D_\Sigma \frac{\partial C_a}{\partial x} \right) + \frac{\partial}{\partial y}\left(vC_a - D_\Sigma \frac{\partial C_a}{\partial y} \right) + \frac{\partial}{\partial z}\left(wC_a - D_\Sigma \frac{\partial C_a}{\partial z} \right) = 0$$

$$D_\Sigma = \frac{1}{\rho}\left(\frac{\mu}{Sc} + \frac{\mu_T}{Sc_T} \right)$$

$\beta = C_a / \rho$ – mass fraction of the combustion products in the mixture

C_a – mass concentration of bastion products at point

D_Σ – effective diffusion coefficient

$Sc,\ Sc_T$ – laminar and turbulent Schmidt numbers

COMPUTATIONAL ALGORITHM

Conservative Approximation of Spatial Operators

The approximations of the spatial operators used in the algorithm are described as applied to the Navier-Stokes equations.
These approximations are underlain by the following identities, which are often used as definitions of the corresponding operators

$$\operatorname{div}\mathbf{g} = -\lim_{\Omega\to 0}\frac{\oint \mathbf{g}\cdot\mathbf{n}\,d\Gamma}{|\Omega|}, \quad \operatorname{grad} p = -\lim_{\Omega\to 0}\frac{\oint p\mathbf{n}\,d\Gamma}{|\Omega|},$$

Approximation of Viscous Operators

$$J(\mathbf{V}) = \int_{\Omega} \left[I(\mathbf{V}) - 2(\mathbf{V} \cdot \Theta) \right] dxdydz$$

$$I(\mathbf{V}) = \mu \left[\frac{4}{3}(u_x^2 + v_y^2 + w_z^2 - u_x v_y - v_y w_z - u_x w_z) + \right.$$

$$\left. + (u_y + v_x)^2 + (u_z + w_x)^2 + (v_z + w_y)^2 \right]$$

Implicit Scheme and Iterative Algorithm

Governing Equations are numerically solved using a two-level fully implicit difference scheme of the form

$$\frac{\varphi^{k} - \varphi^{k-1}}{\Delta t} + A^{-1} H(\varphi^{k}) = 0,$$

$$H(\varphi^{k}) = T(\varphi^{k}) + V(\varphi^{k}).$$

$$A = E + \frac{1}{d}\tilde{V}', \quad d = \|T'\|,$$

φ – grid vector function involving all unknown functions

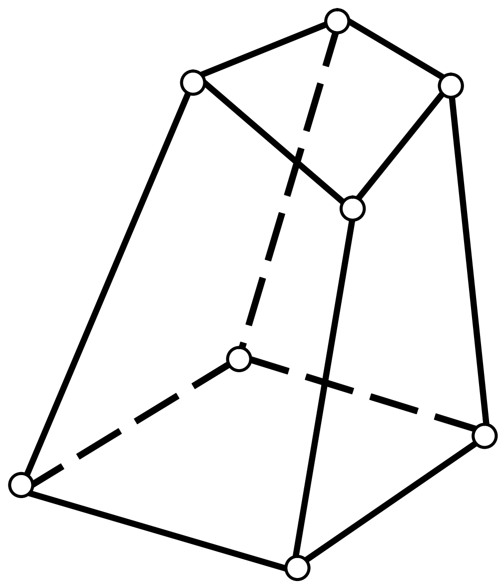
k – the time level index

Δt – time step; A – operator improving the convergence of the iterations

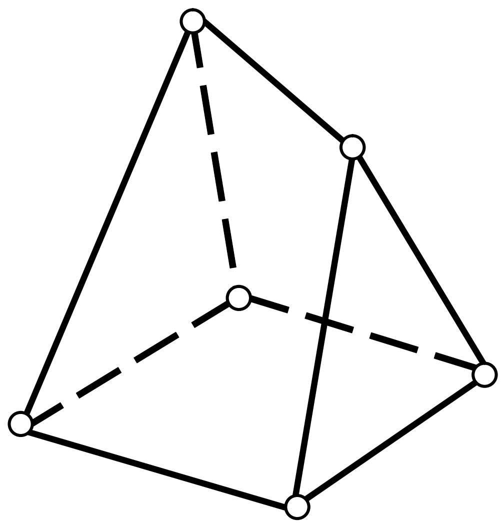
$\boldsymbol{H}$ – operator containing all spatial difference derivatives

Numerical Grid

The grid algorithm generates a three-dimensional boundary-conforming structured meshes with hexahedral cells. Degenerate (pentahedral) cells could be used on the axis of symmetry of the domain.



Hexahedral cell

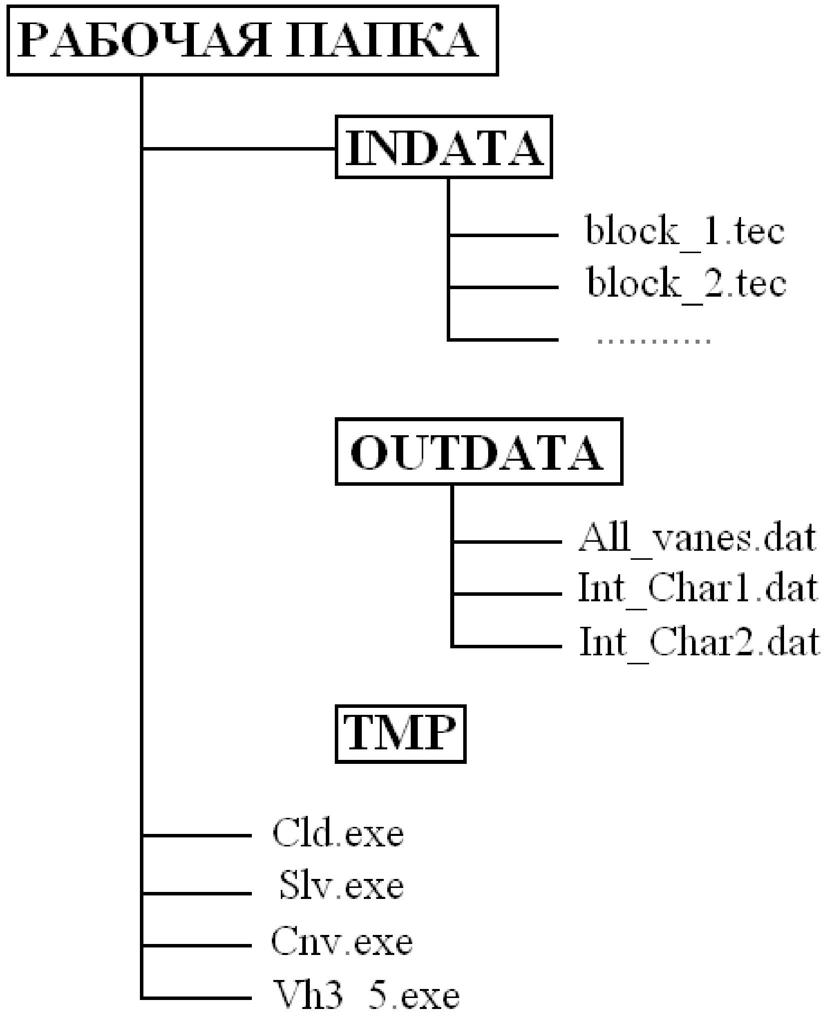


Pentahedral cell

Grid Requirements

1) The mapping to a parametric parallelepiped used in structured mesh generation must be continuously differentiable and its Jacobian must not vanish.
2) To resolve the boundary layers, the mesh must be refined toward the solid walls. Moreover, the transverse (to the flow direction) mesh size near these surfaces can be 10^{-4} and less of the characteristic length of the problem.
3) The grid lines near the walls must be nearly orthogonal to them. Wherever possible, the mesh cells must be similar to parallelepipeds.
4) The numerical grid must be quasi-uniform in the sense that, as the number of grid nodes tends to infinity, the difference between the characteristic lengths of neighboring cells tends to zero faster than the lengths themselves. Anyway, the ratio of the characteristic lengths of neighboring cells must not be too large.

Code's Structure

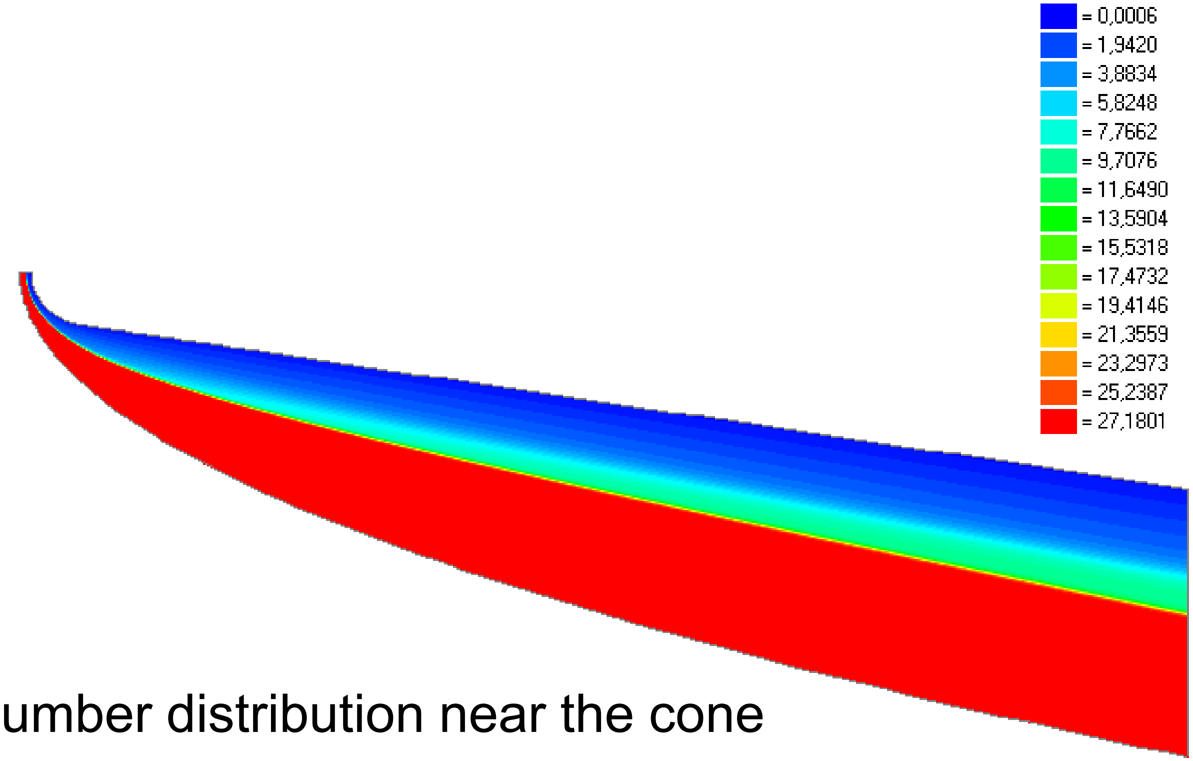


Flow past a Spherically Blunted Cone

Semiapex angle of 9°

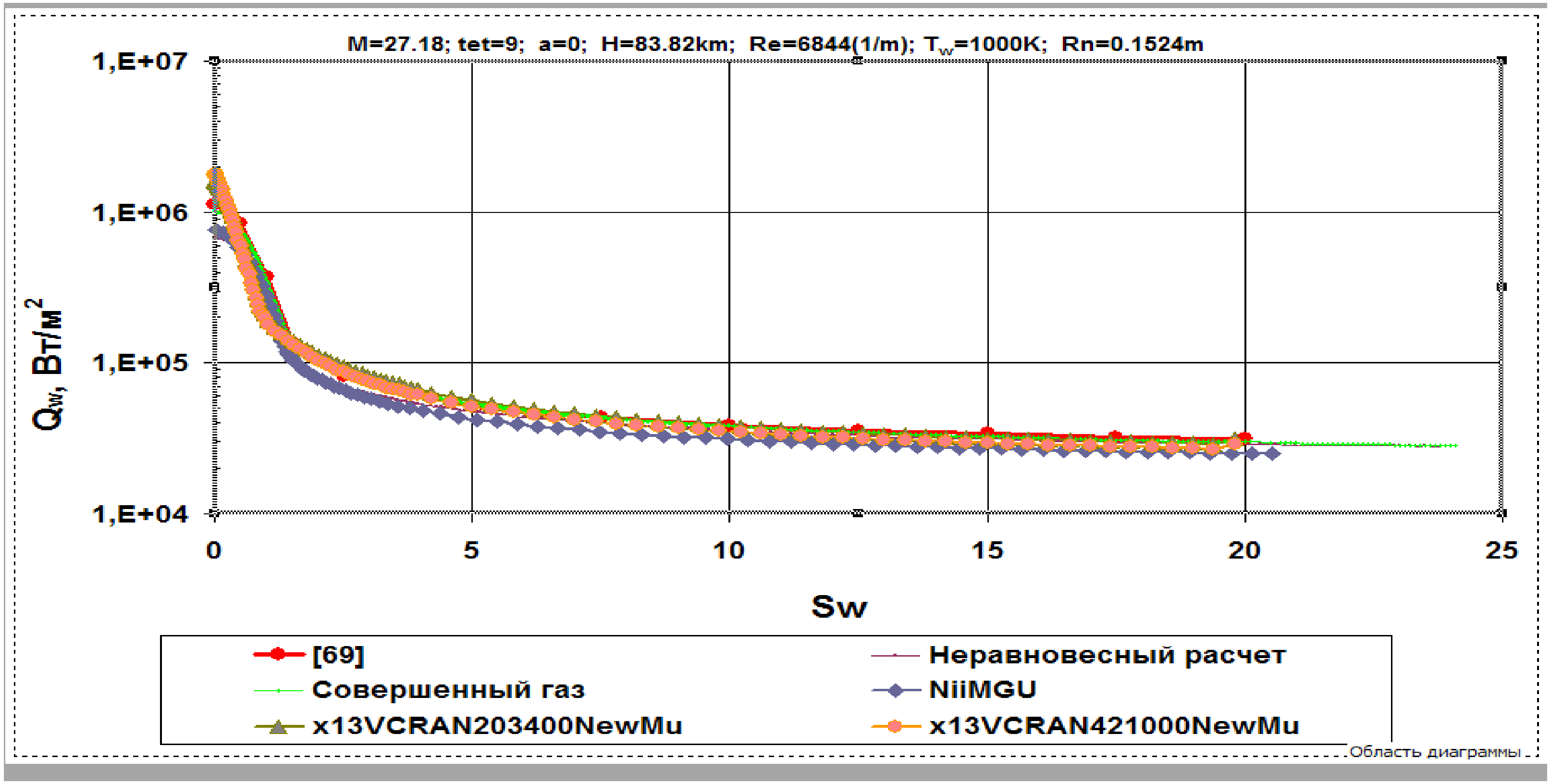
Freestream Mach number 27

Spherical cap of radius 0.15 m



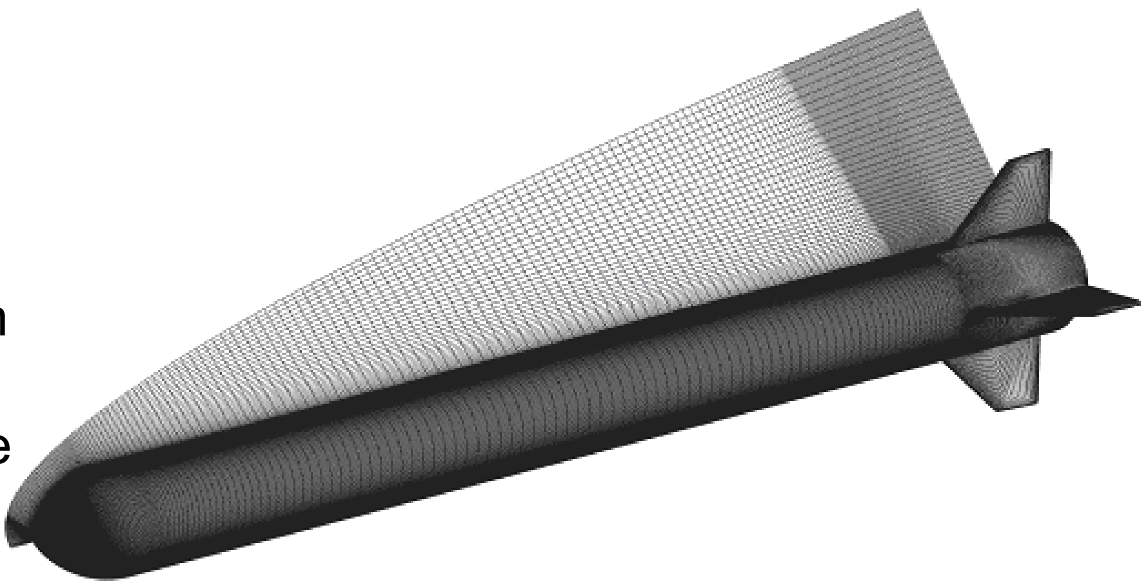
Mach number distribution near the cone

Heat flux on the cone surface vs. the distance



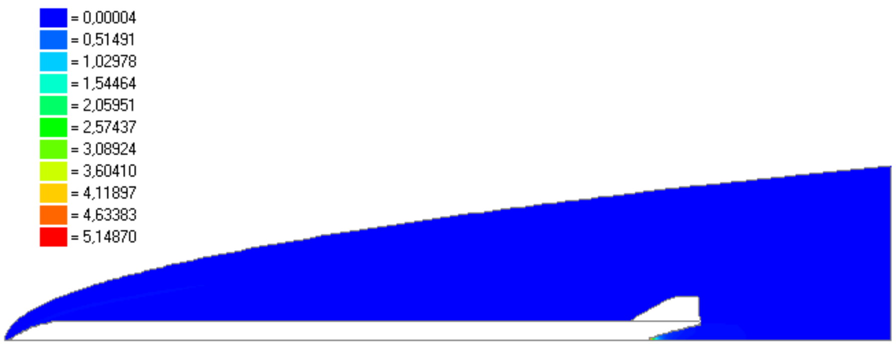
Gas Flow around a Flight Vehicle with Allowance for the Flow/Exhaust Jet Interaction

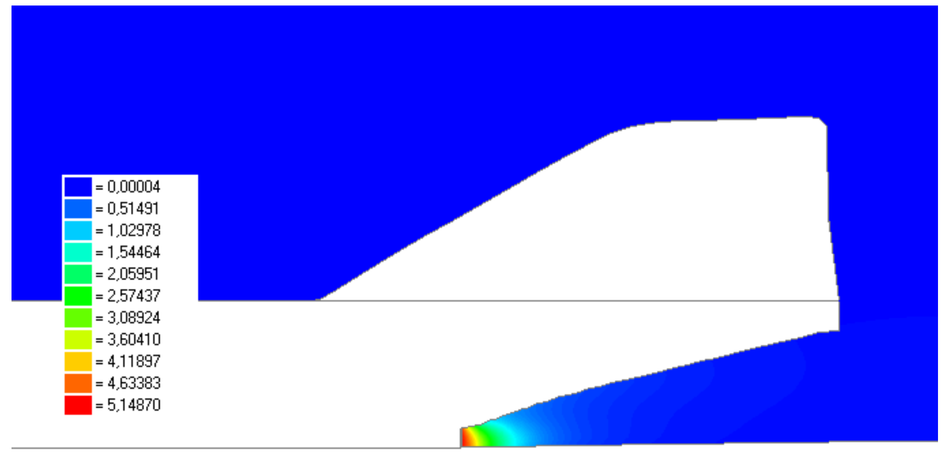
It is assumed that fuel combustion products are exhausted from the nozzle of the vehicle. The exhaust jet has a high temperature. In the general case, the physical characteristics of the jet differ noticeably from those of the ambient air. The task is to determine the flow parameters near the vehicle and some of its integral characteristics



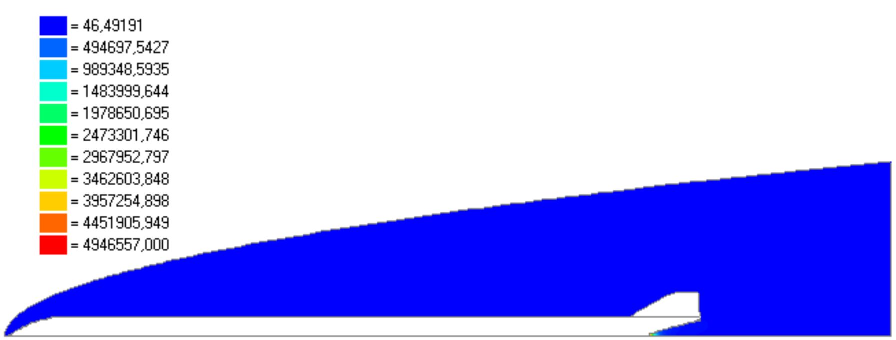
Field Distributions in a longitudinal cross section of the computational domain containing a rudder

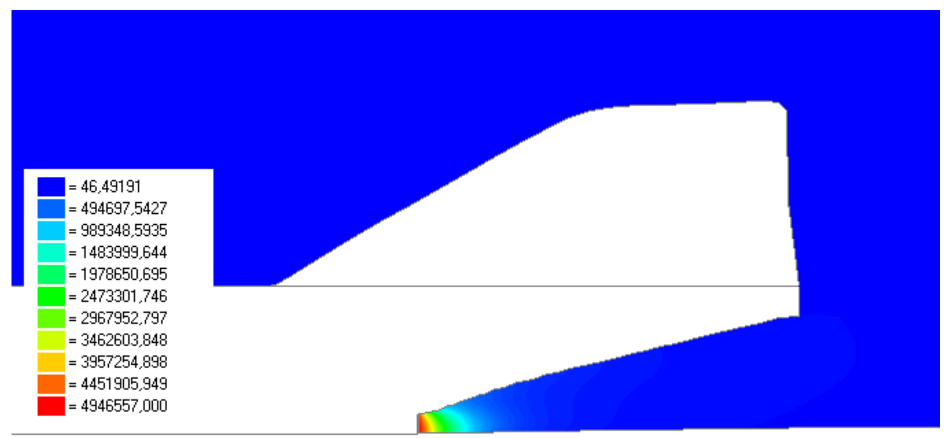
Density





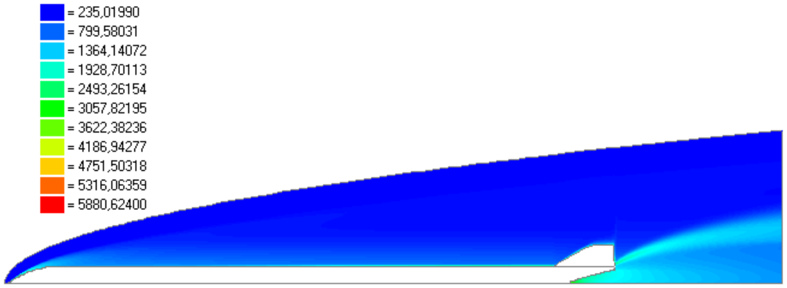
Pressure

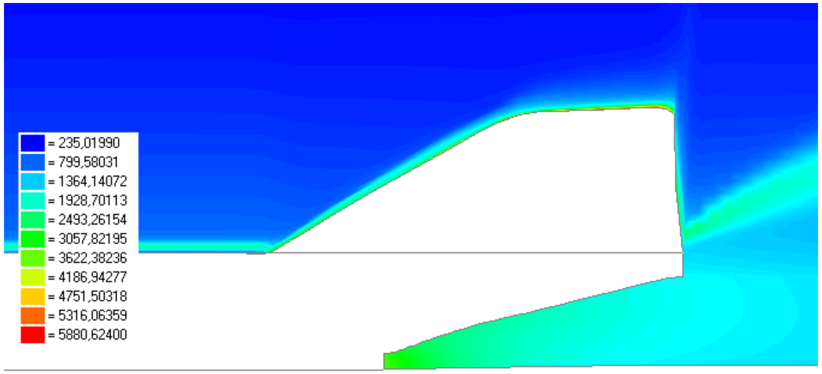




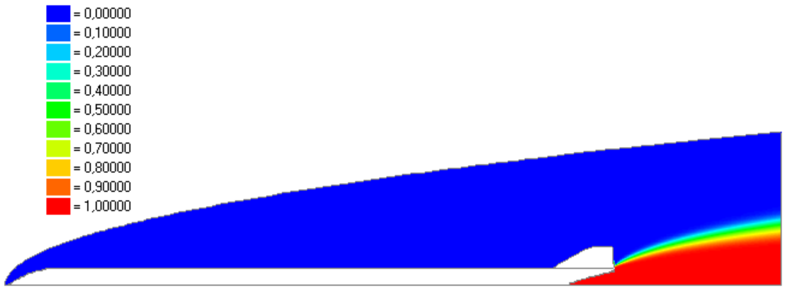
Field Distributions in a longitudinal cross section of the computational domain containing a rudder

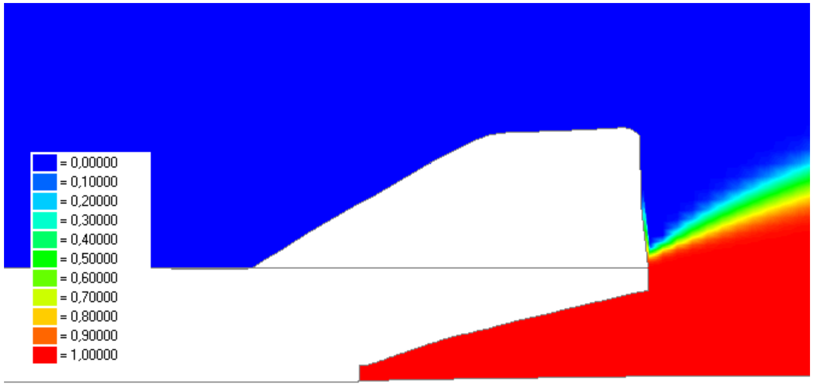
Temperature





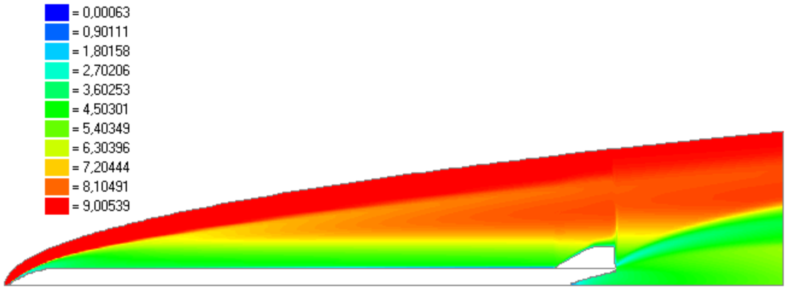
Fraction

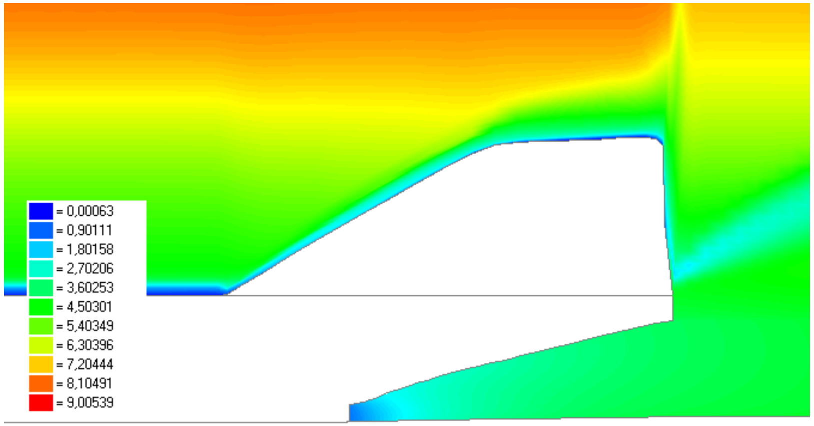




Field Distributions in a longitudinal cross section of the computational domain containing a rudder

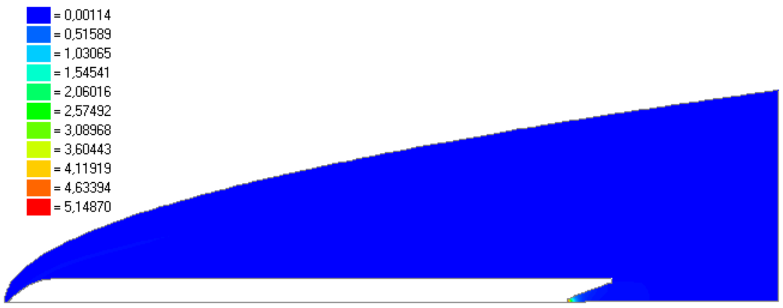
Max number



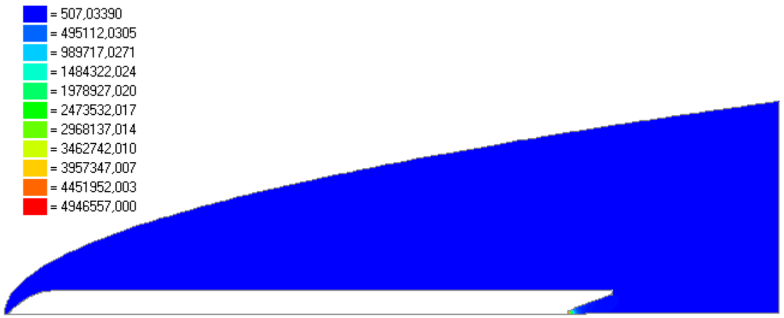


Field Distributions in a longitudinal cross section of the computational domain between rudders

Density

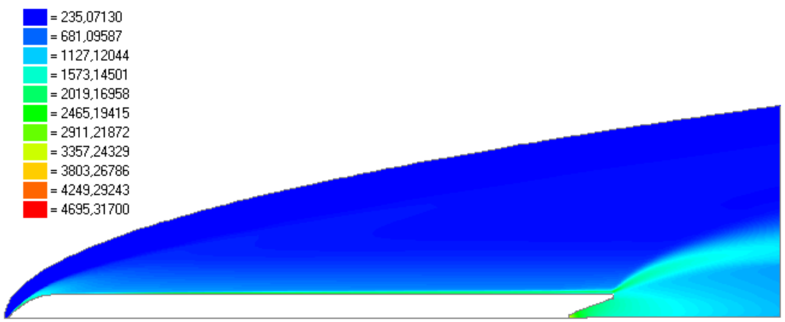


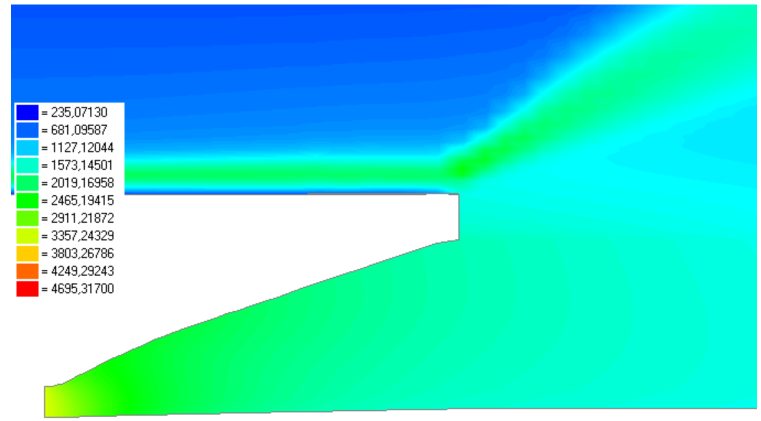
Pressure



Field Distributions in a longitudinal cross section of the computational domain between rudders

Temperature





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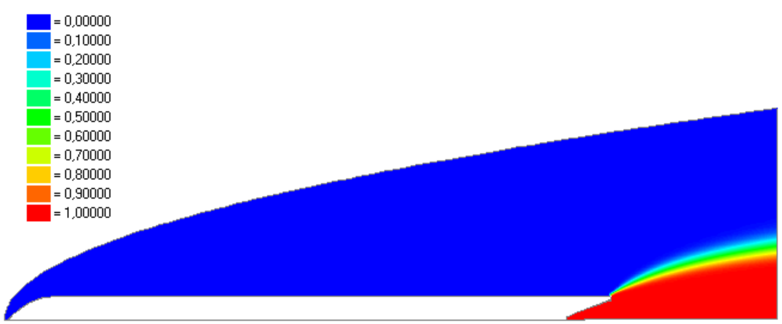
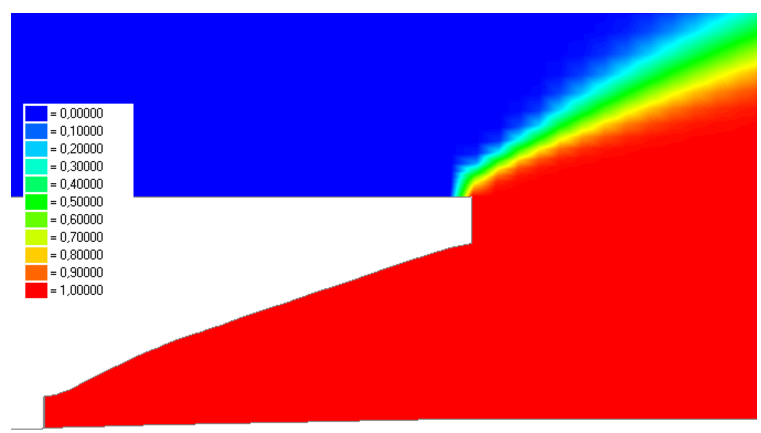
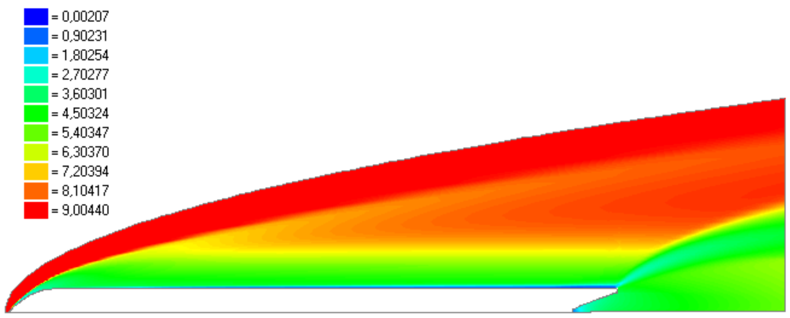
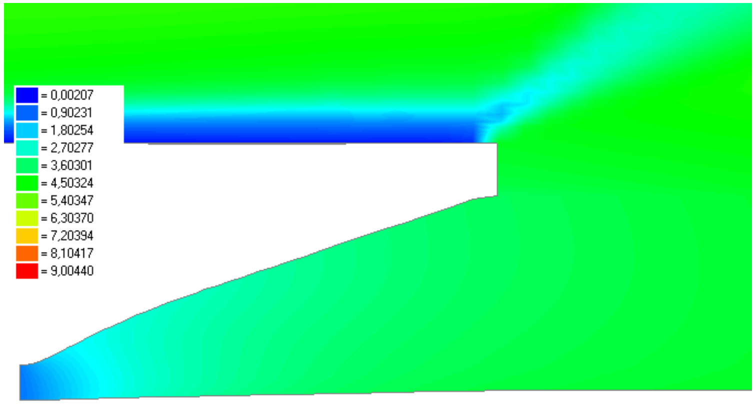




Field Distributions in a longitudinal cross section of the computational domain between rudders

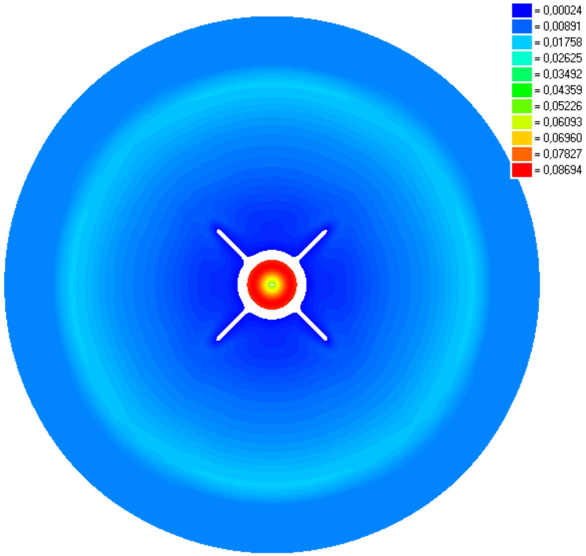
Max number



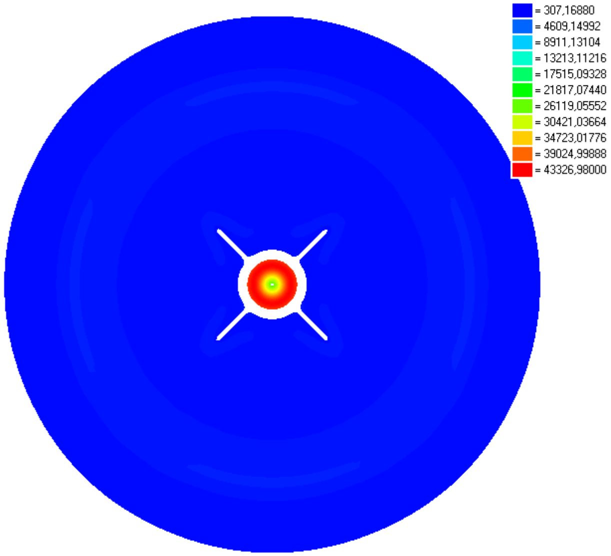


Field Distributions in a transverse cross section of the computational domain near the rear end

Density

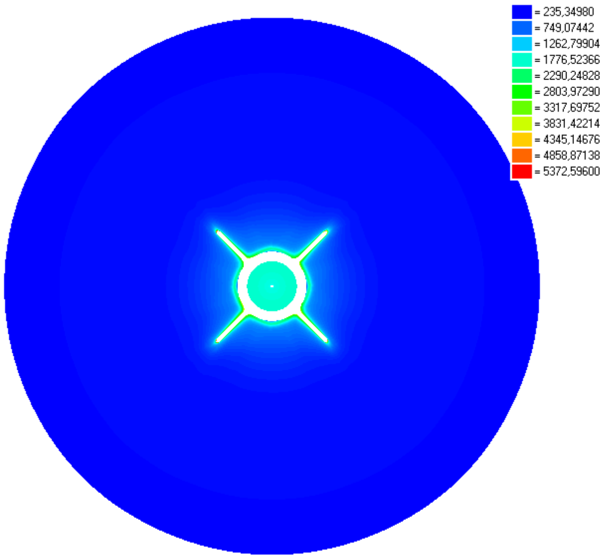


Pressure



Field Distributions in a transverse cross section of the computational domain near the rear end

Temperature



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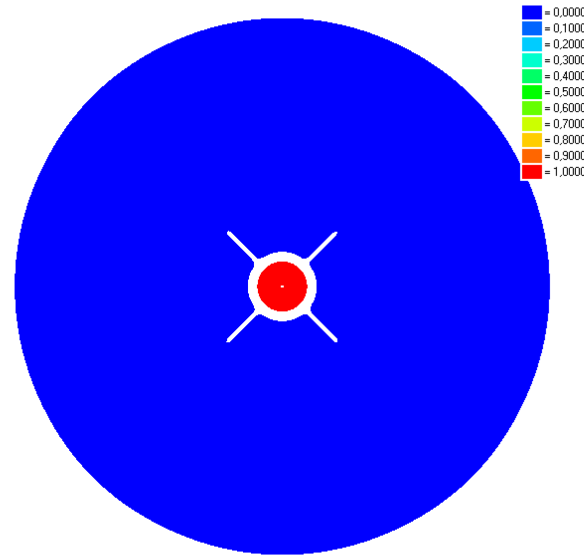

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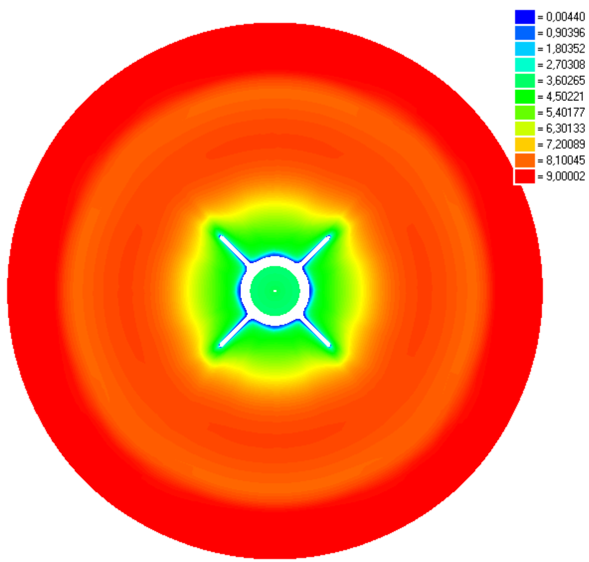
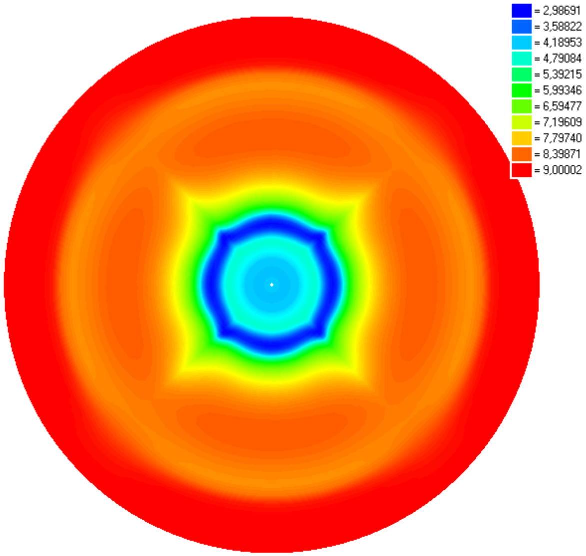


Field Distributions in a transverse cross section away from the rear end

Max number



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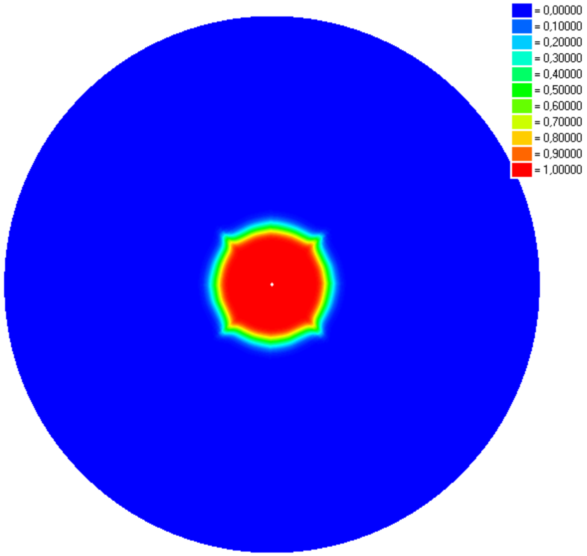
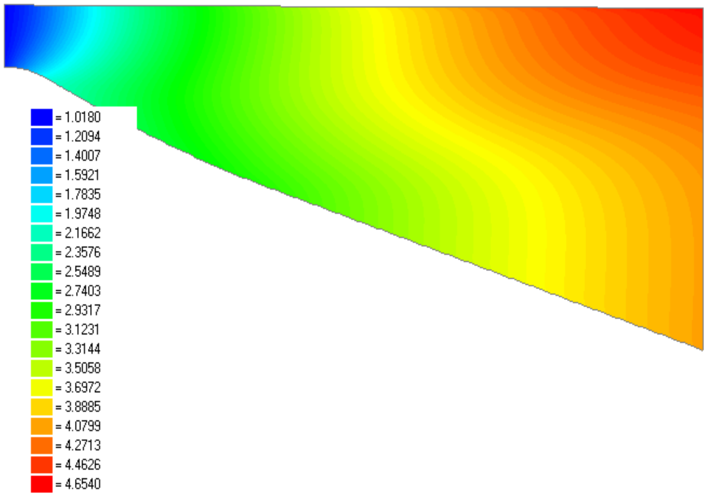
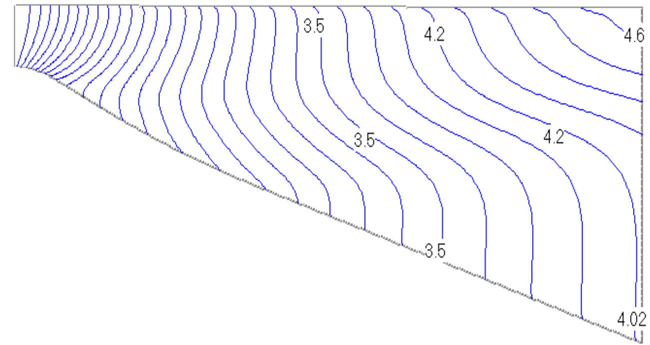


Calculation the aerodynamic parameters in device nozzle

Max number





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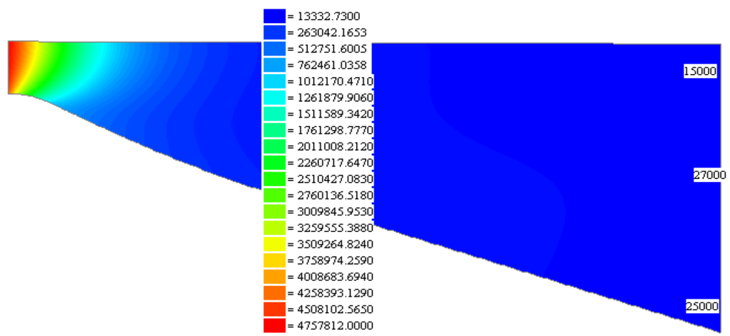
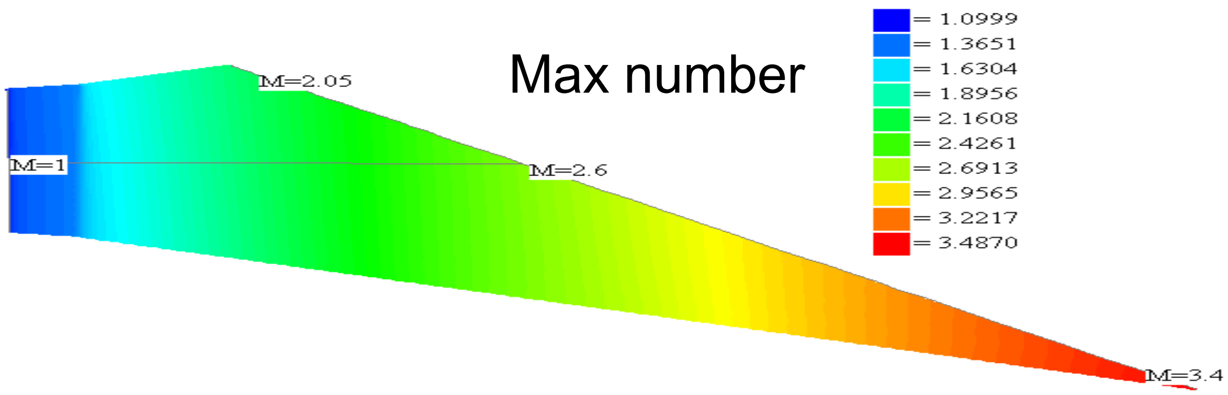
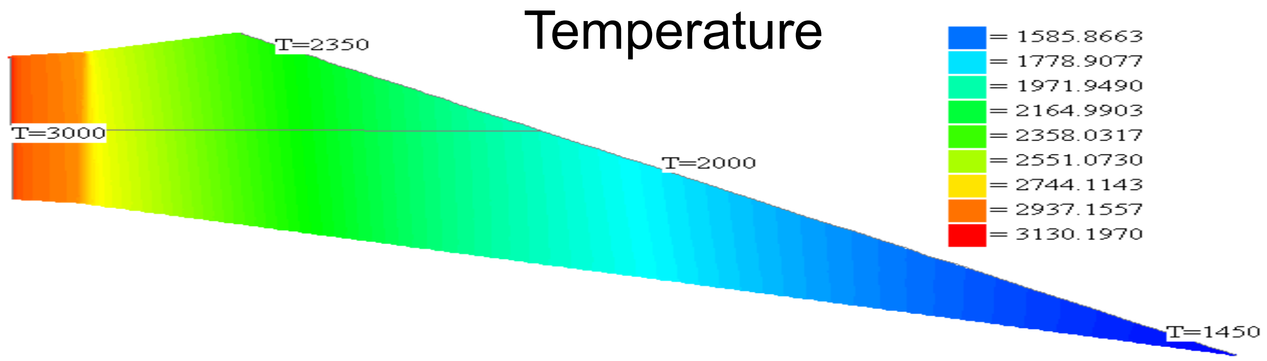


Газодинамические параметры в скошенном сопле





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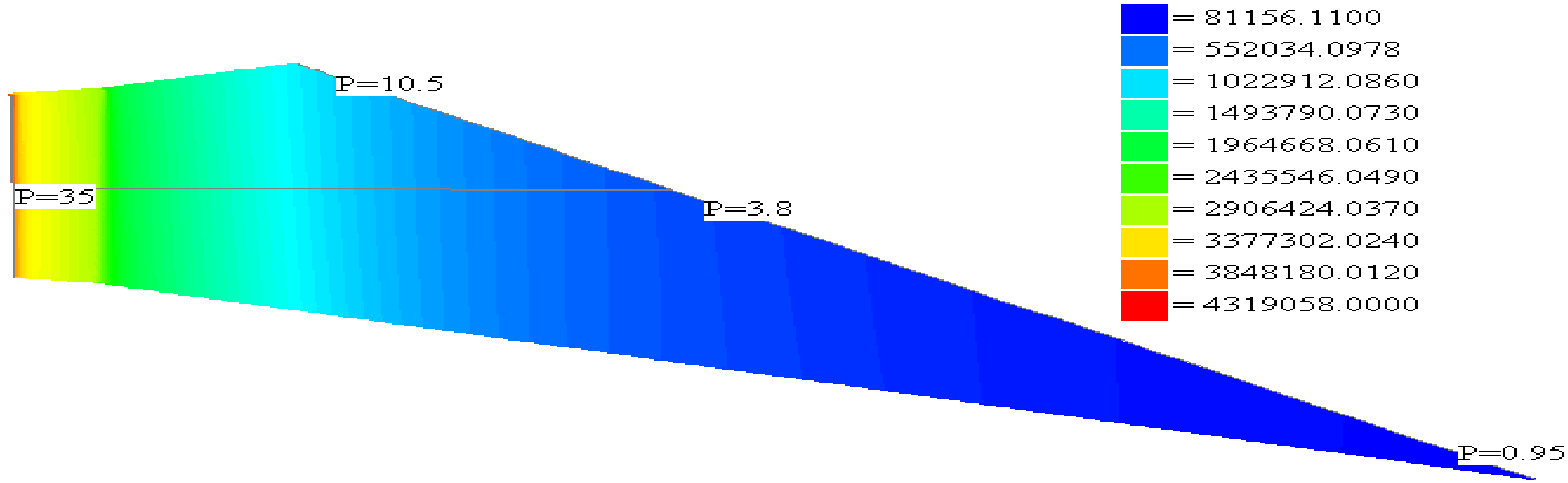
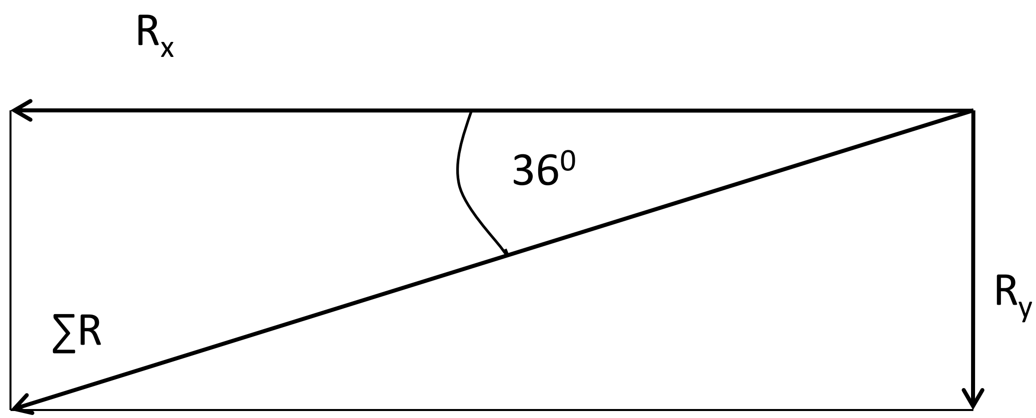
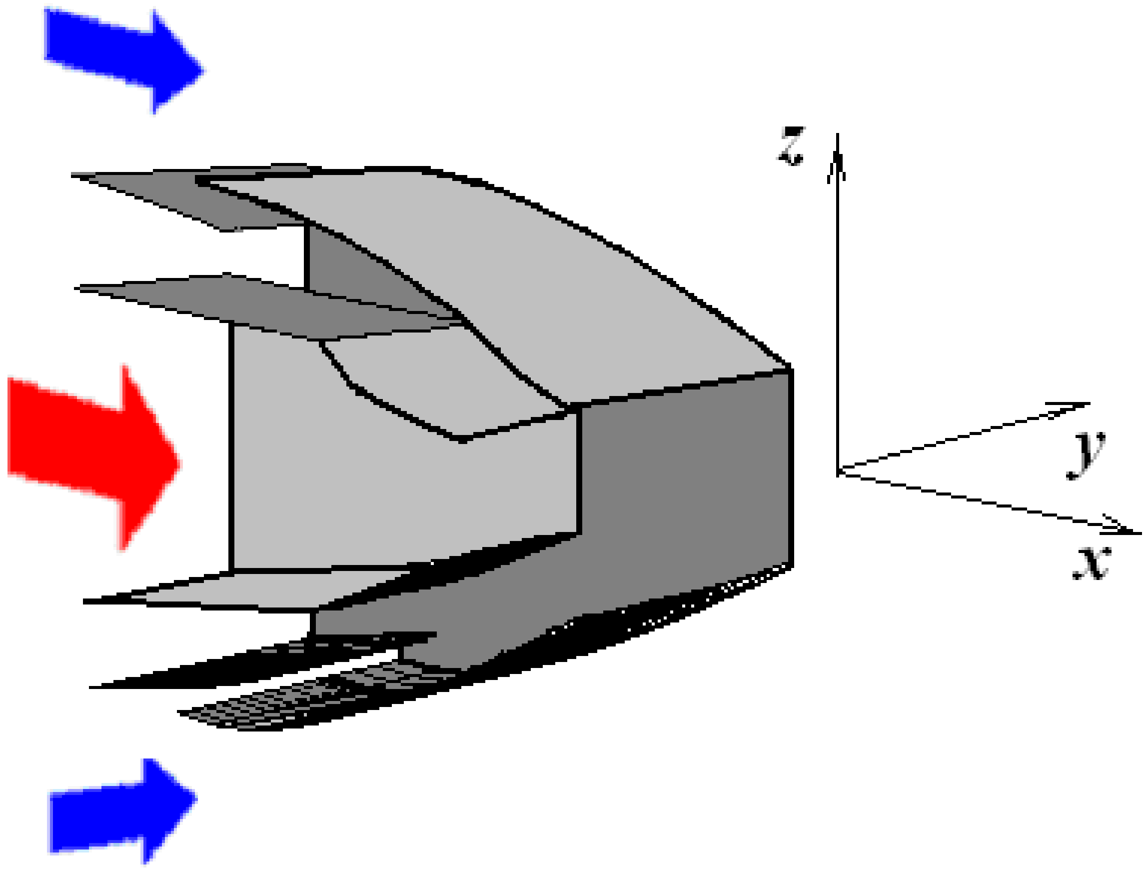


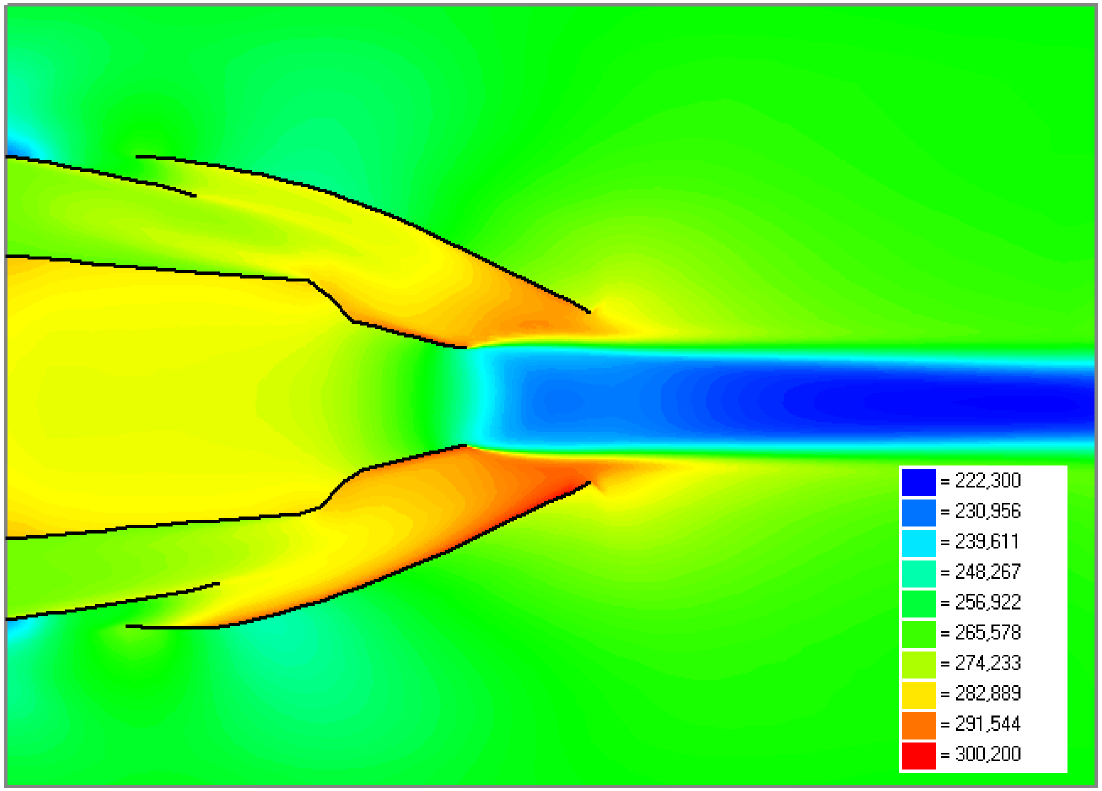
Отклонение вектора тяги



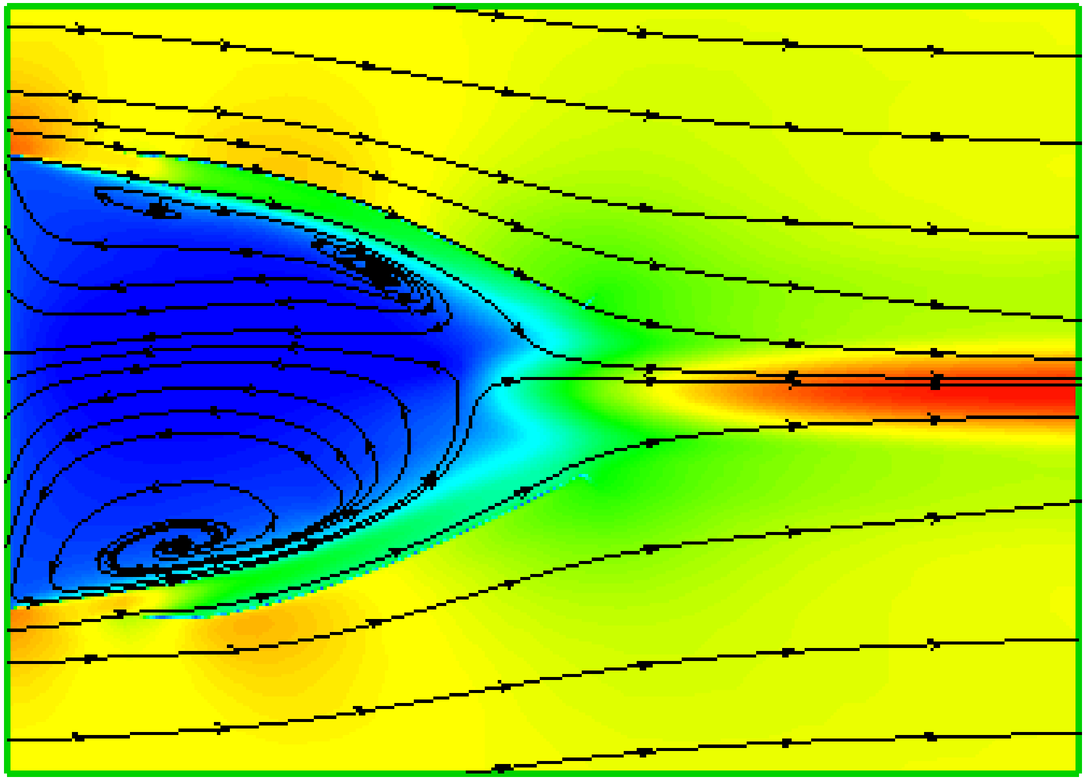
Three-Dimensional Turbulent Gas Flows in Complex Nozzle Systems



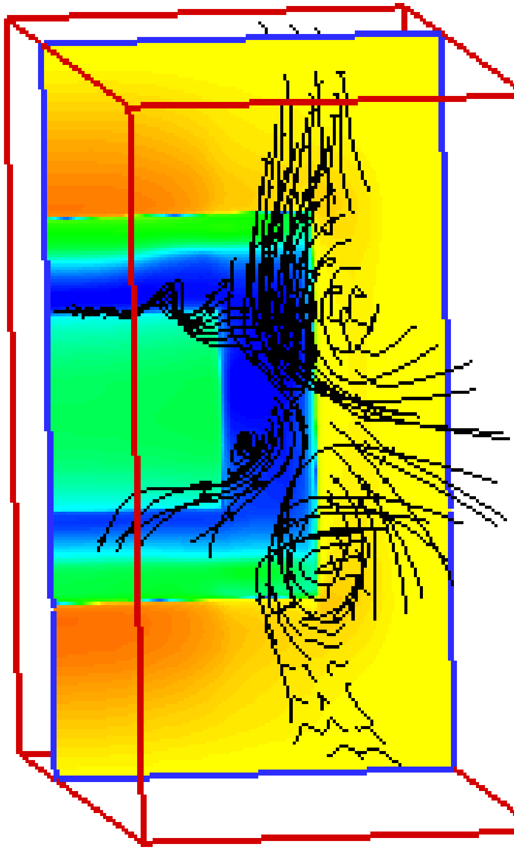
Temperature distribution in the middle section



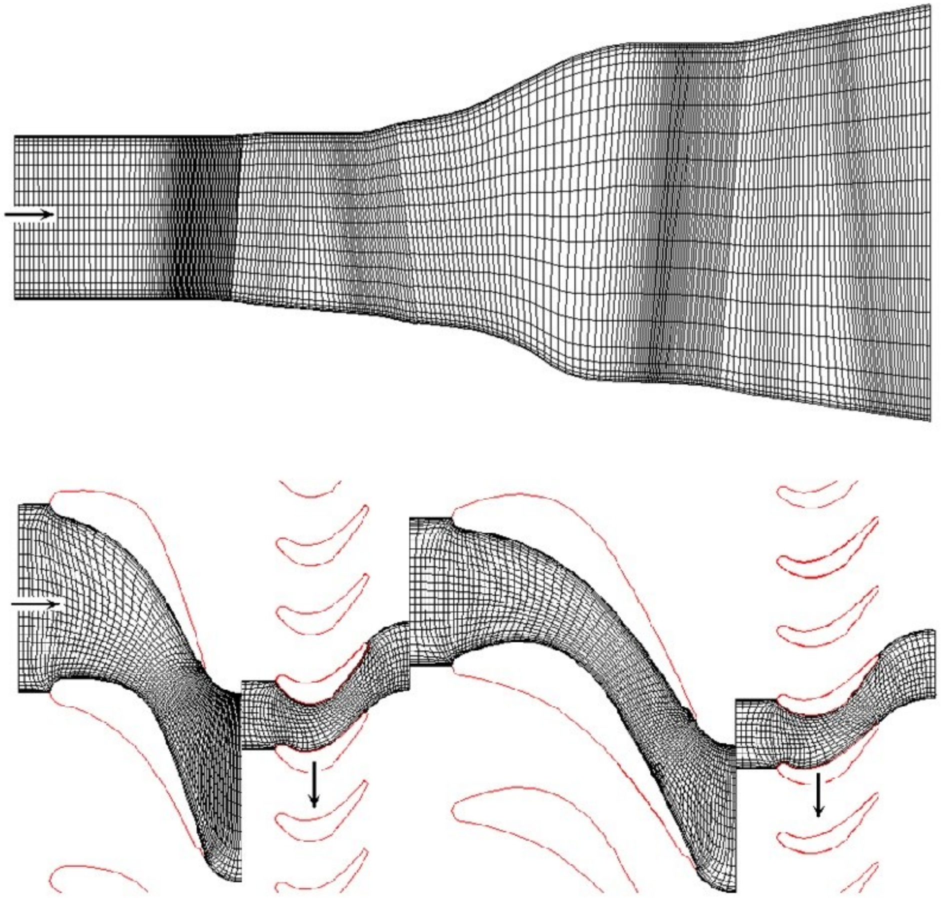
Streamlines in a vertical plane through the interwall spacing



Streamlines for the flow behind the nozzle exit

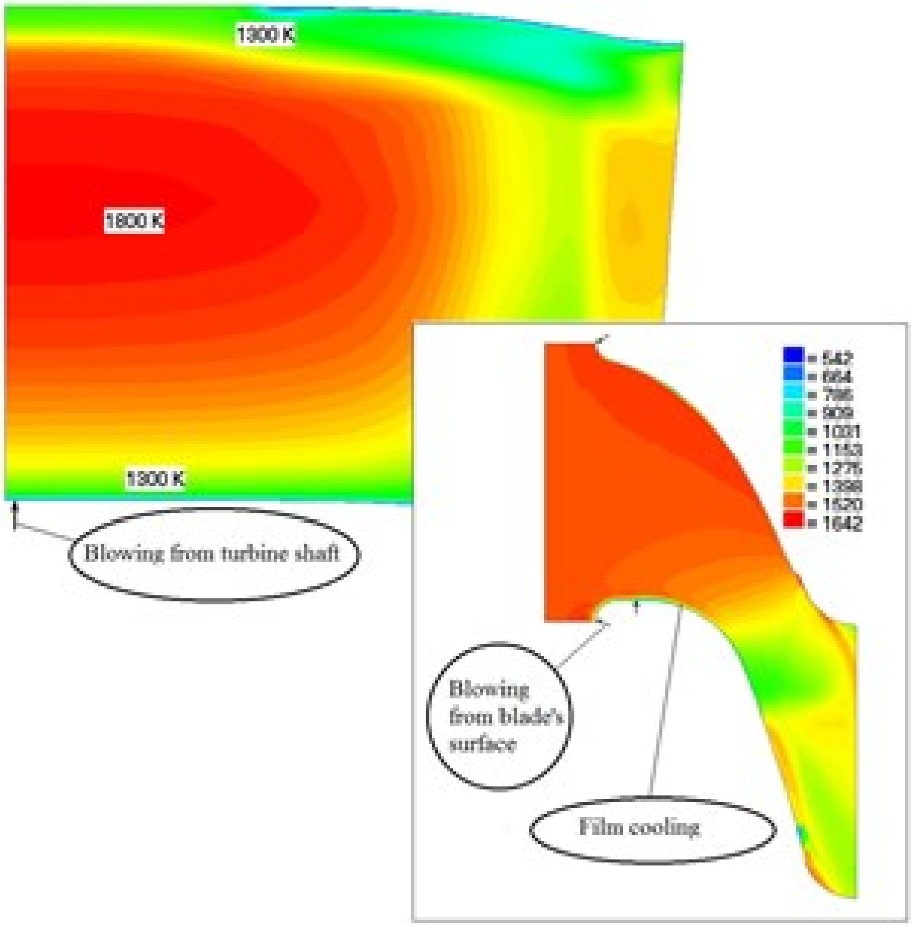


Simulation of gas flow in cooled axial turbines

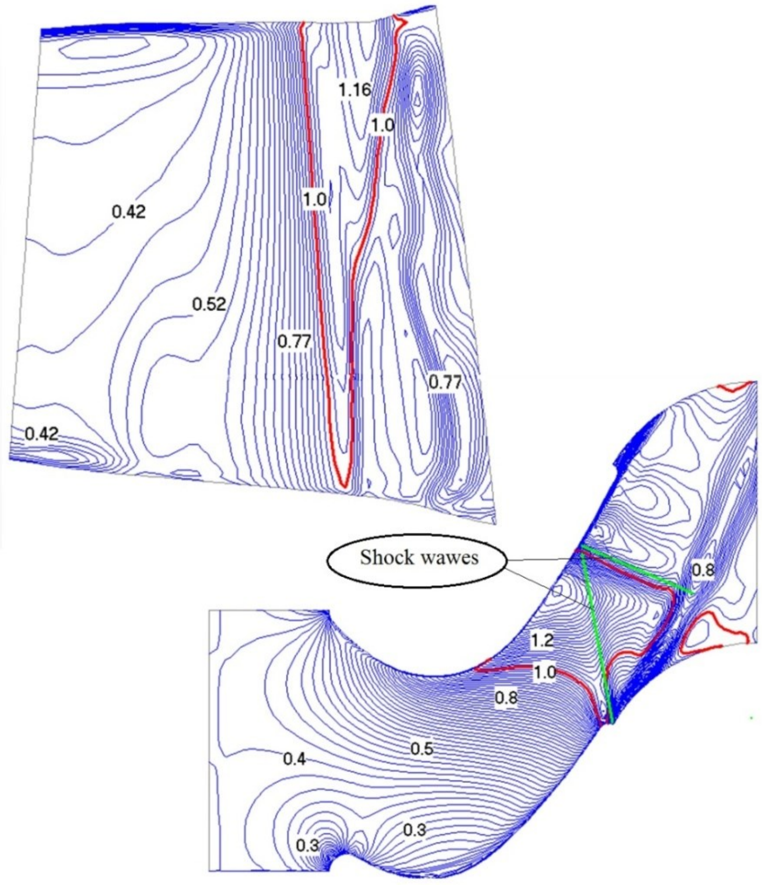


Numerical grid in middle radial and axial plans

Temperature in first stage stator of turbine in middle radial and axial plans



Mach number in first stage rotor of turbine in middle radial and axial plans



CONCLUSIONS

The submitted results show the ability to use the software package for solving wide range of stationary and non stationary aerodynamic problems

THANK YOU FOR ATTANTION