CFD Investigations of Spatial Arc Kinetic Influence on Fuel Burning-Out in the “Tornado” Combustor

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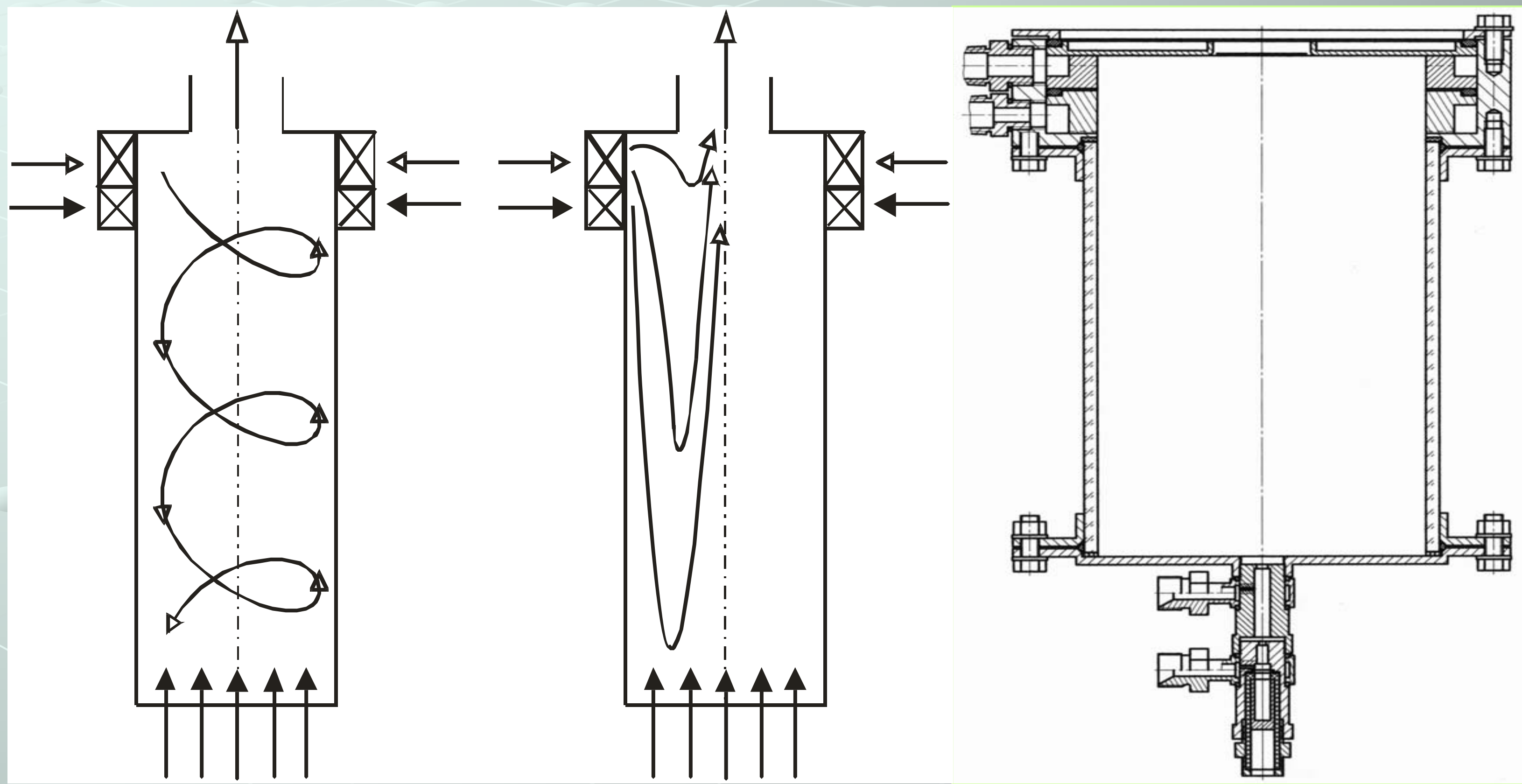
Objectives

- CFD investigation of aerodynamic reacting flow structure in “Tornado” combustor with different air excess coefficients
- Proposal of the simplified method for the CFD-modeling of the plasma spatial arc
- Examination of the different effects of plasma stabilization on the flow structure and emission levels in the “Tornado” combustor
- Analysis of efficiency of the plasma spatial arc application in reverse vortex chamber for combustion process improvement

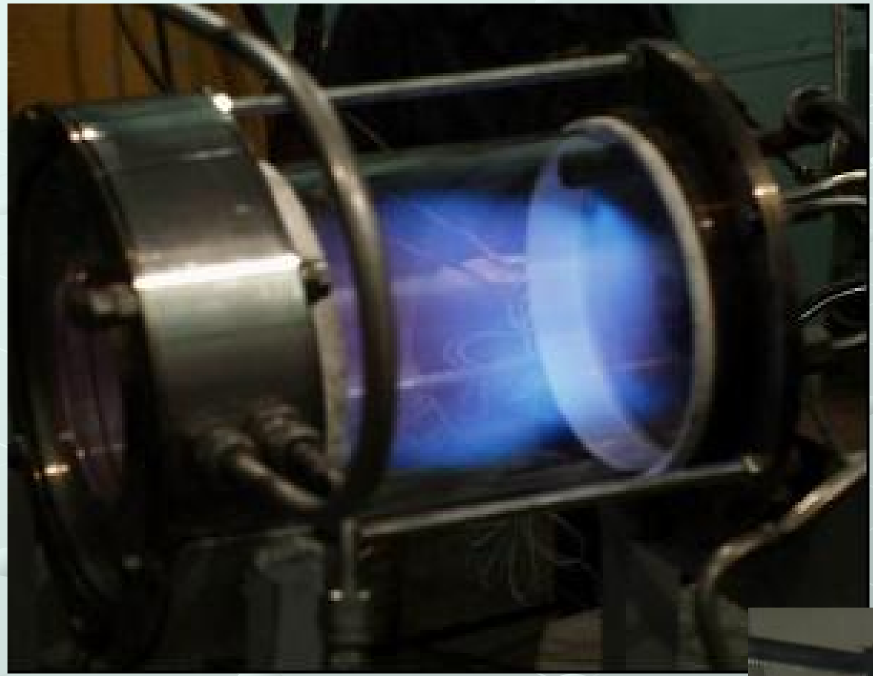
Contents

Previous design of full-sized "Tornado" combustor

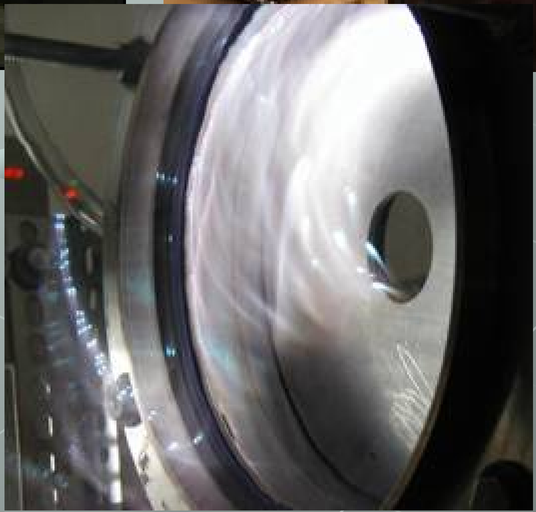


Aerodynamic scheme of the reverse vortex flow

Preliminary test of full-sized "Tornado" combustor

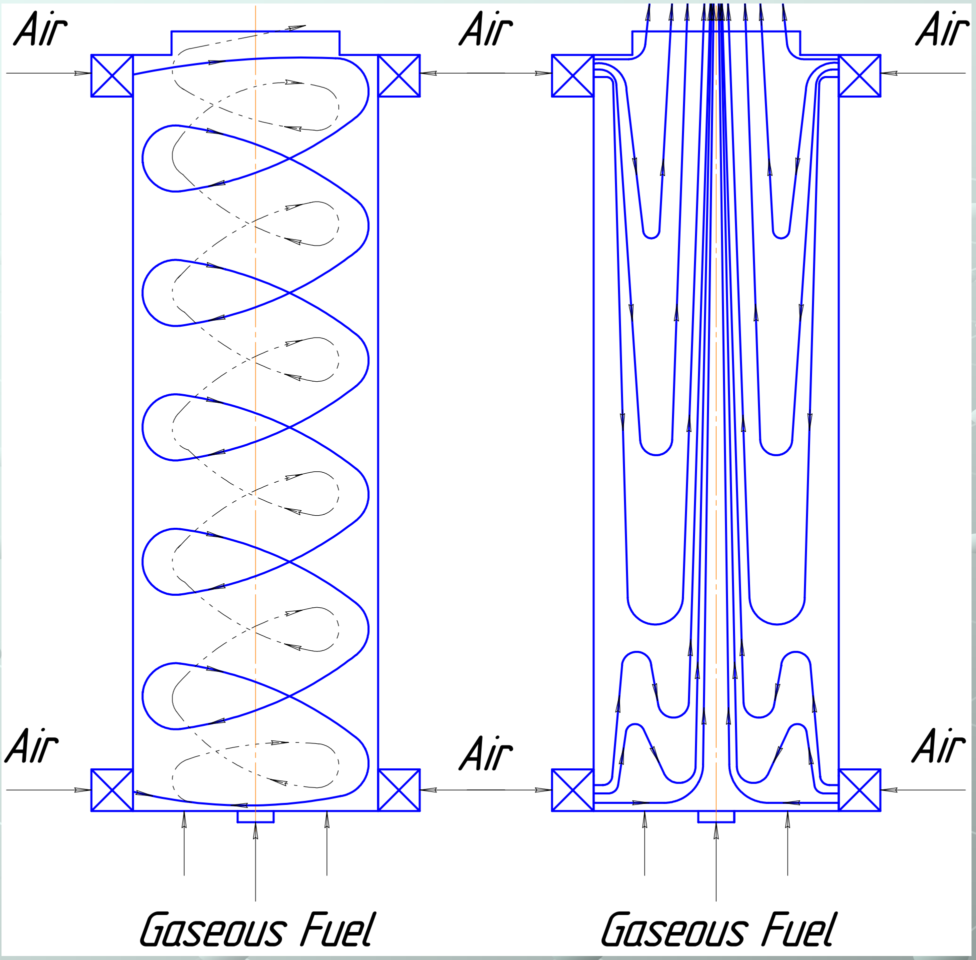


The high voltage rotating spatial arc of non thermal plasma was generated during the tests near the outlet nozzle

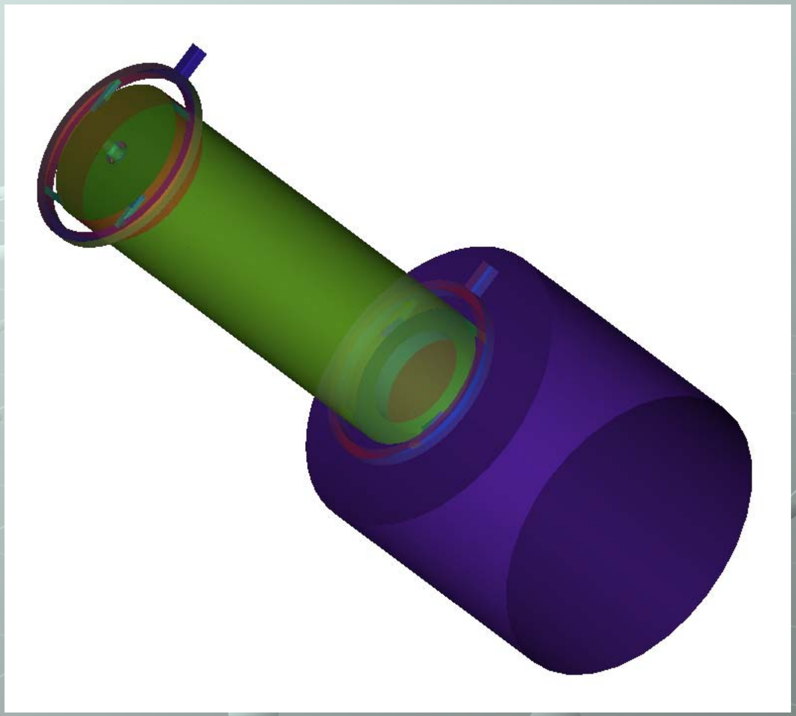


The vortex structure can be sharply defined on the photos

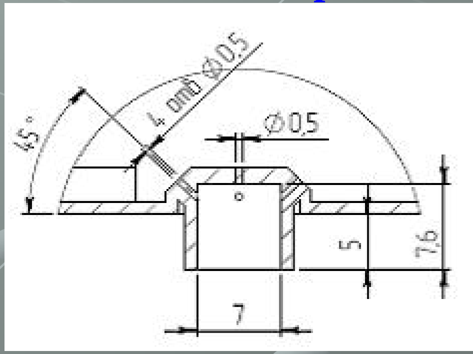
Design of the "Tornado"-pilot



Aerodynamic scheme of the reverse vortex flow



3D model of reverse vortex combustor for numerical experiments



Central fuel injector

Mathematical model

A number of numerical simulations for tornado-pilot were made to investigate the influence of spatial arc on chemical processes inside the device. For modeling of physical and chemical processes inside the RVC with spatial arc a generalized method based on numerical solution of the combined conservation and transport equations for multi-component chemically reactive turbulent system was employed. These are the equation for conservation of mass and conservation of momentum and energy. The RNG *k*-ε- model was chosen as it is more responsive to the effects of rapid strain and streamline curvature than the standard *k*-ε -model

1. RNG *k*-ε -model

Equation for conservation of mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m$$

Equation for conservation of momentum

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla p + \nabla \cdot (\tau_{st}) + \rho \vec{g} + \vec{F}$$

Equation for conservation of energy

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\vec{\upsilon}(\rho E + p)) = -\nabla \cdot \vec{J}_q + S_h$$

Stress tensor

$$\tau_{st} = \mu[(\nabla \vec{v} + \nabla \vec{v}^T) - \frac{2}{3}\nabla \cdot \vec{v} I$$

Transport equations for the RNG *k*-ε-model

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}(\alpha_k \mu_{eff} \frac{\partial k}{\partial x_j}) + G_k + G_b - \rho \varepsilon - Y_M + S_k$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}(\alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j}) + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon}\rho \frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon$$

Additional term in the ε equation

$$R_\varepsilon = \frac{C_\mu \rho \eta^3 (1 - \eta / \eta_0)}{1 + \beta \eta^3}\frac{\varepsilon^2}{k}$$

Equation for turbulent viscosity

$$d(\frac{\rho^2 k}{\sqrt{\varepsilon \mu}}) = 1.72 \frac{\hat{\nu}}{\sqrt{\hat{\nu}^3 - 1 + C_\nu}} d\hat{\nu}$$

Mathematical model

As the turbulent flows in “Tornado” combustor are characterized by eddies with a wide range of length and time scales. The largest eddies are typically comparable in size to the characteristic length of the mean flow. The smallest scales are responsible for the dissipation of turbulence kinetic energy. In LES, large eddies are resolved directly, while small eddies are modeled. Large eddy simulation (LES) thus falls between DNS and RANS in terms of the fraction of the resolved scales. The governing equations employed for LES are obtained by filtering the time-dependent Navier-Stokes equations in either Fourier (wave-number) space or configuration (physical) space. The filtering process effectively filters out the eddies whose scales are smaller than the filter width or grid spacing used in the computations. The resulting equations thus govern the dynamics of large eddies.

2. LES model

Filtered variable

$$\bar{\phi}(x) = \int_D \phi(x')G(x,x')dx'$$

Filtering the Navier-Stokes equations

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho \bar{u}_i) = 0$$

$$\frac{\partial}{\partial t}(\rho \bar{u}_i) + \frac{\partial}{\partial x_j}(\rho \bar{u}_i \bar{u}_j) = \frac{\partial}{\partial x_j}(\mu \frac{\partial \sigma_{ij}}{\partial x_j}) - \frac{\partial \bar{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j}$$

Stress tensor

$$\sigma_{ij} = [\mu(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i})] - \frac{2}{3}\mu \frac{\partial \bar{u}_l}{\partial x_l}\delta_{ij}$$

Subgrid-scale stress

$$\tau_{ij} - \frac{2}{3}k_{sgs}\delta_{ij} = -2C_k k_{sgs}^{1/2}\Delta_f \bar{S}_{ij}$$

Turbulence kinetic energy , transport equation

$$k_{sgs} = \frac{1}{2}\left(\overline{u_k^2} - \bar{u}_k^2\right); \qquad \frac{\partial \bar{k}_{sgs}}{\partial t} + \frac{\partial \bar{u}_j \bar{k}_{sgs}}{\partial x_j} = -\tau_{ij}\frac{\partial \bar{u}_i}{\partial x_j} - C_\varepsilon \frac{k_{sgs}^{3/2}}{\Delta_f} + \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k_{sgs}}{\partial x_j}\right)$$

Eddy viscosity

$$\mu_t = C_k k_{sgs}^{1/2}\Delta_f$$

Rate-of-strain tensor

$$\bar{S}_{ij} = \frac{1}{2}(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i})$$

Filter size

$$\Delta_f = V^{1/3}$$

Combustion model

Transport equation for chemical species $$\frac{\partial}{\partial t}(\rho Y_i) + \nabla(\rho \vec{\upsilon} Y_i) = -\nabla \cdot \vec{J}_i + R_i + S_i$$

Arrhenius law for chemical reaction $$k_{f,r} = A_r T^{\beta_r} e^{-E_r / RT}$$

3. The Eddy-Dissipation-Concept (EDC) Model

This model assumes that reaction occurs in small turbulent structures, called fine scales. Species react in the fine structures over a timescale. Reaction proceed over the time scale, governed by Arrhenius rates and are integrated numerically using ISAT algorithm

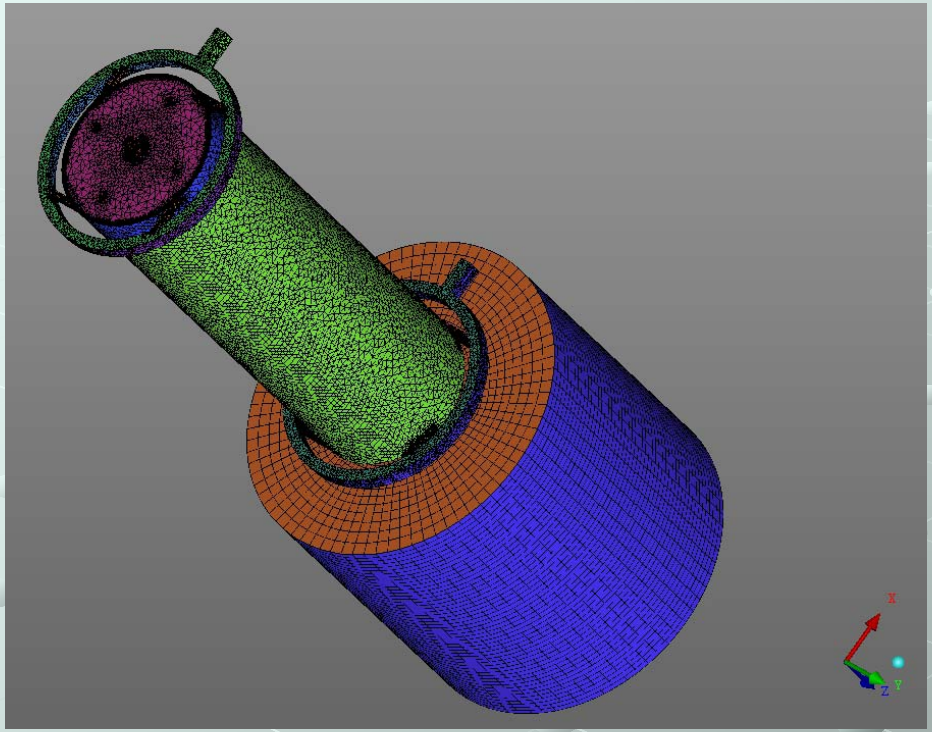
Volume fraction of the fine scales $$\xi^* = C_\xi \left(\frac{\nu\varepsilon}{k}\right)^{3/4}, \quad C_\xi = 2{,}1377$$

Time scales $$\tau^* = C_\tau \left(\frac{\nu}{\varepsilon}\right)^{1/2}, \quad C_\tau = 0{,}4082$$

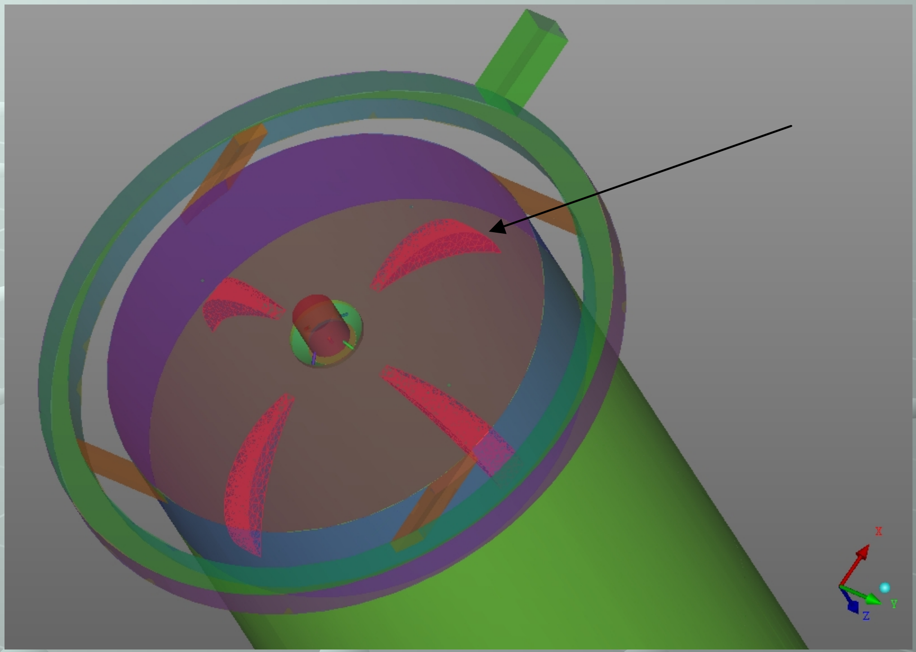
Net source of species *i* by chemical reaction $$R_i = \frac{\rho(\xi^*)^2}{\tau^*\left[1-(\xi^*)^3\right]}(Y_i^* - Y_i)$$

Fine-scale species mass fraction Y_i^* after reacting over the time τ^*

Computational Mesh and plasma approaches



Hybrid computation grid consists
of 0.75 million elements:
329909 tetras
133240 hexas
275449 prisms
12441 pyramids



Plasma torch was modeled as four separate rotating volumes nearby fuel injection region

Plasma approaches

1. The spatial arc was modeled using rotating reference frame approach in steady cases and the moving mesh was used in unsteady with LES-turbulence model.

Equation for conservation of momentum for the rotating volumes

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla\cdot(\rho\vec{v}_r\vec{v}) = -\nabla p + \nabla\cdot(\tau_{st}) + \rho\vec{g} + \vec{F}$$

Relative velocity

$$\vec{v}_r = \vec{v} - (\vec{\Omega}\times\vec{r}),$$

$\vec{\Omega}$ -angular velocity

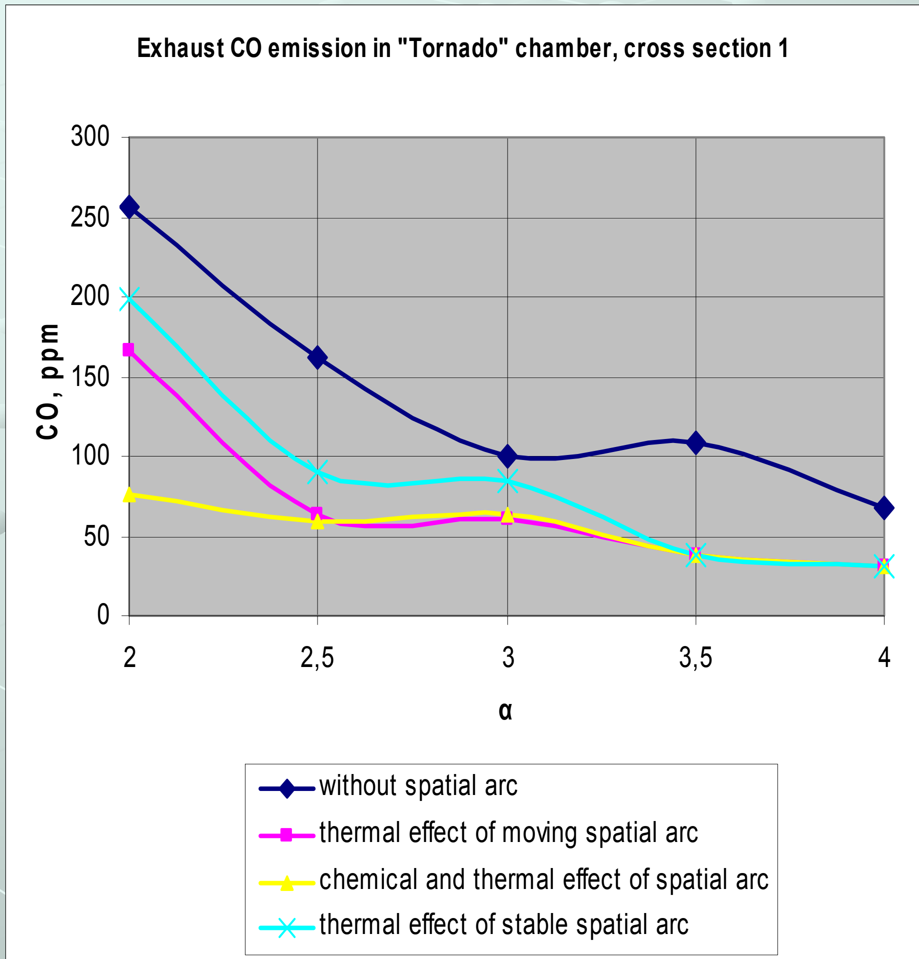
$\vec{r}$ -position vector in the rotating frame

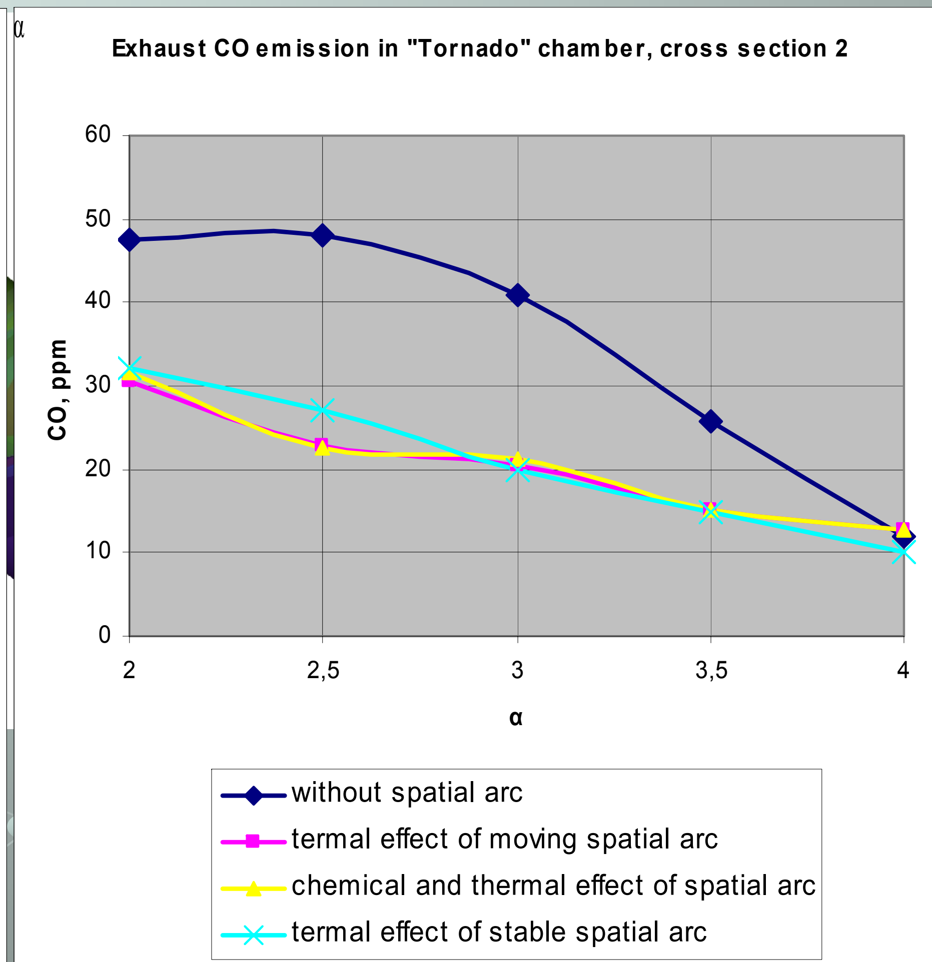
2. The spatial arc is assumed as the thermal source of 100 W. That means that the source term in equation for conservation of energy $S_h = 7.42e{+}07\ W/m^3$.

3. The reaction mechanism (Arrhenius rates) in spatial arc differs from the whole combustor volume:

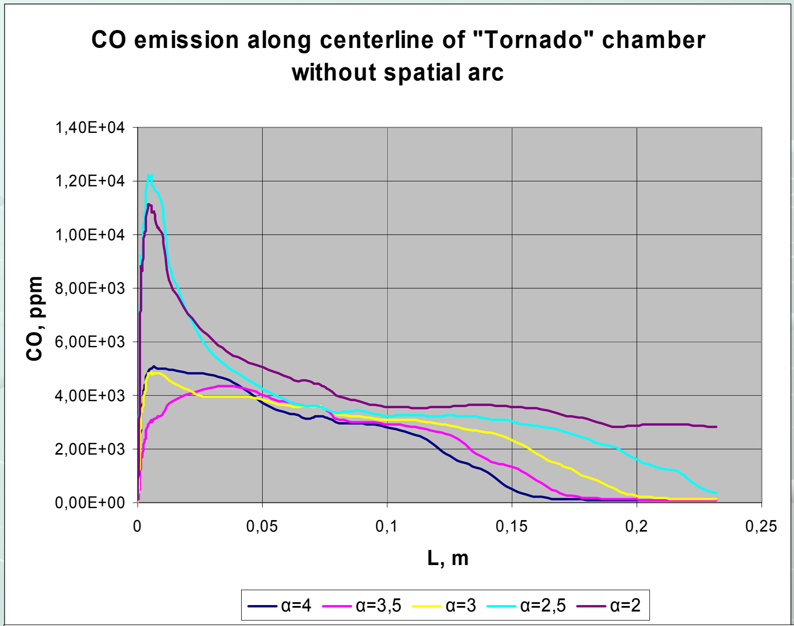
Reaction	A	E_a	β	Reaction order			
$CH_4 + 1{,}5O_2 \rightarrow CO + 2H_2O$	5.012e+11	2e+08	0	CH_4	0.7	O_2	0.8
$CO + O_2 \rightarrow 1{,}5CO_2$	2.239e+12	1.7e+08	0	CO	1	O_2	0.25
$CH_4 + 1{,}5O_2 \rightarrow CO + 2H_2O$	5.012e+11	2e+08	0	CH_4	0.7	O_2	0.8
$CO + O_2 \rightarrow 1{,}5CO_2$	2.239e+12	1.19e+08	0	CO	1	O_2	0.25

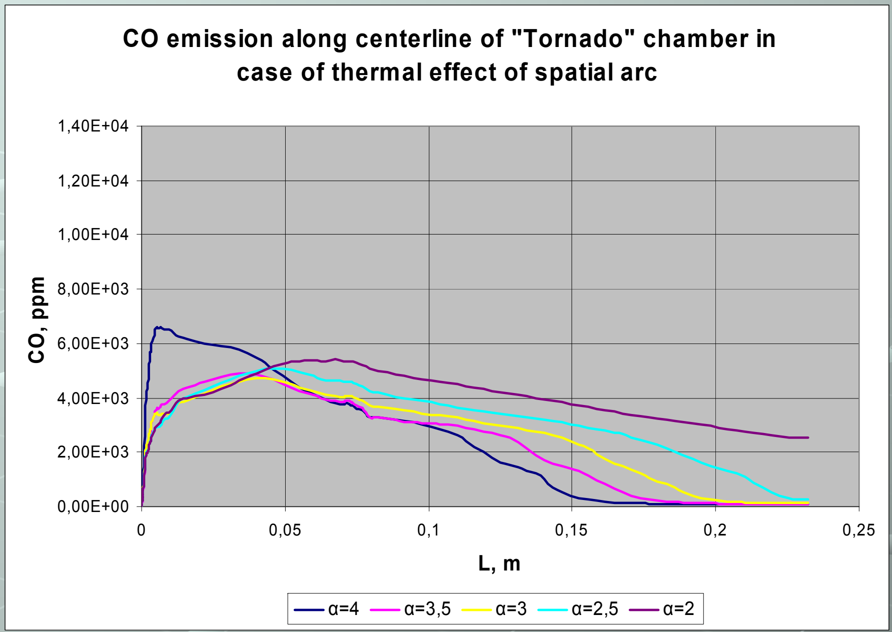
Results of the numerical experiments (investigation of different plasma effects on burnout process in combustor)

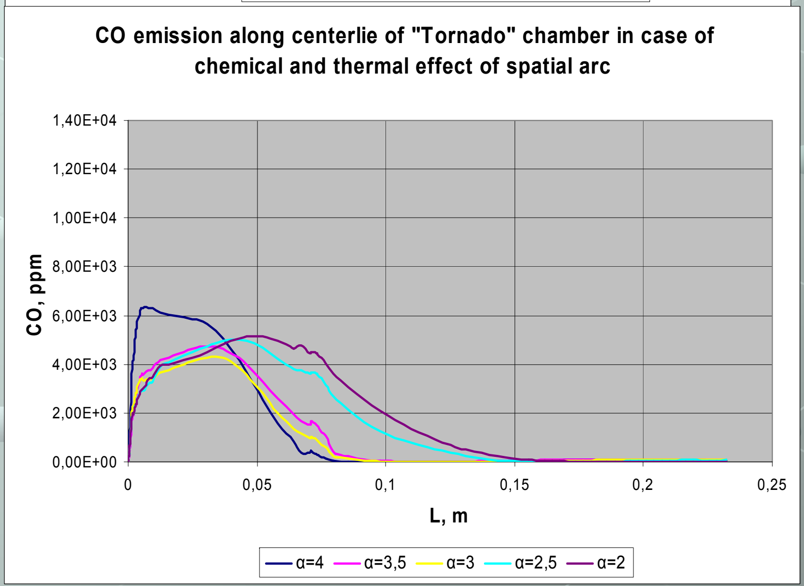




Results of the numerical experiments



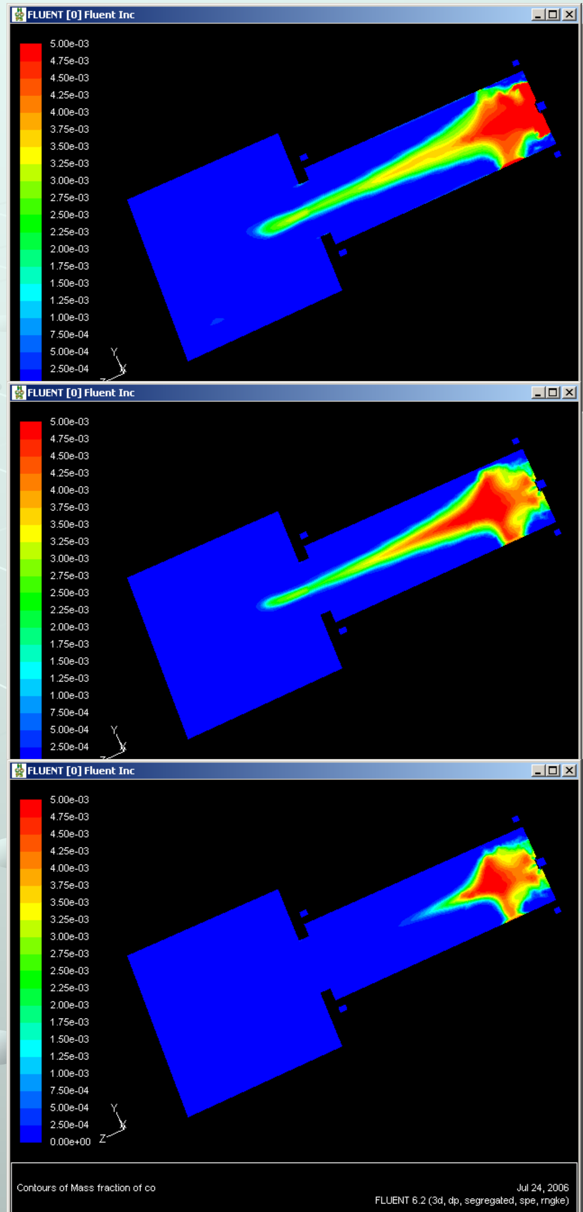


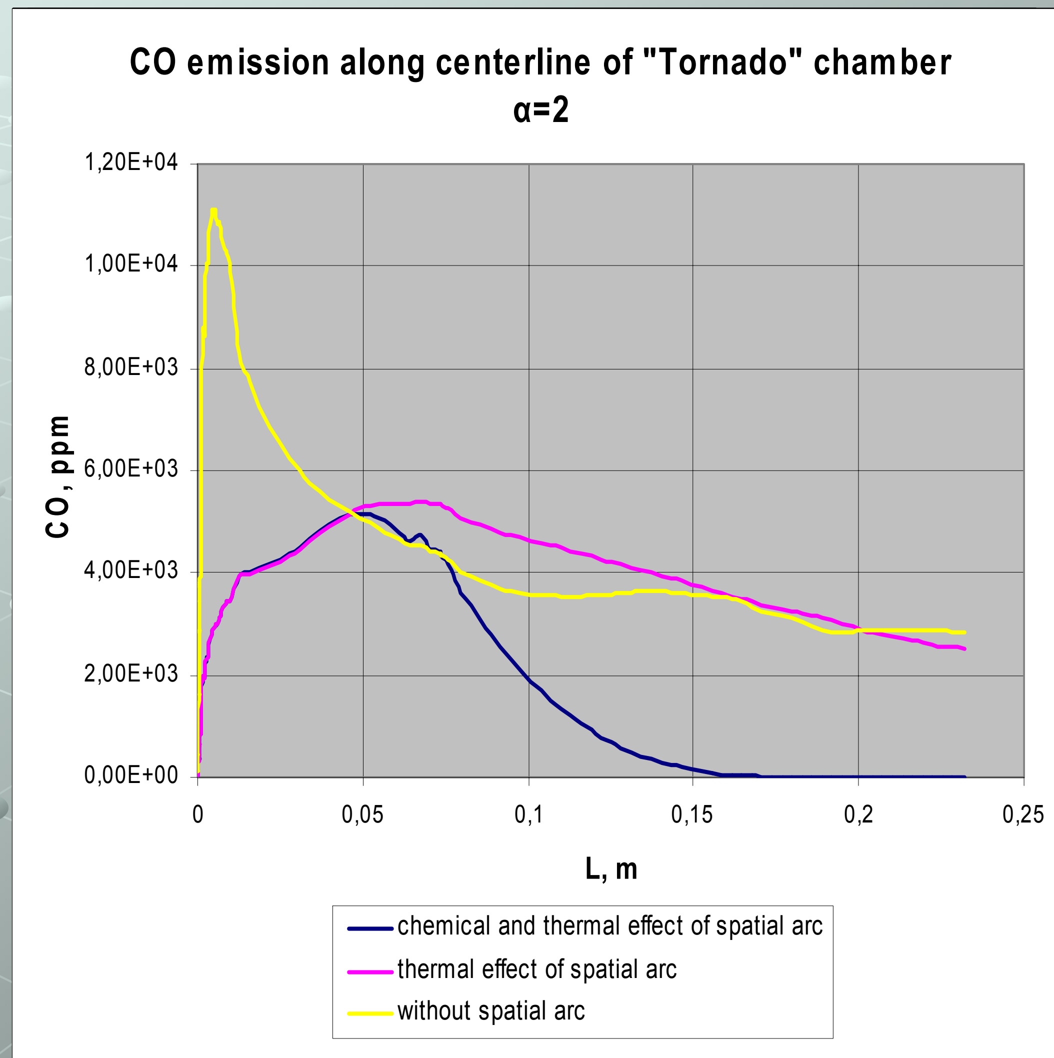


Carbon monoxide distribution along the “Tornado”-pilot centerline without spatial arc, with thermal, and with thermal and chemical plasma effects.

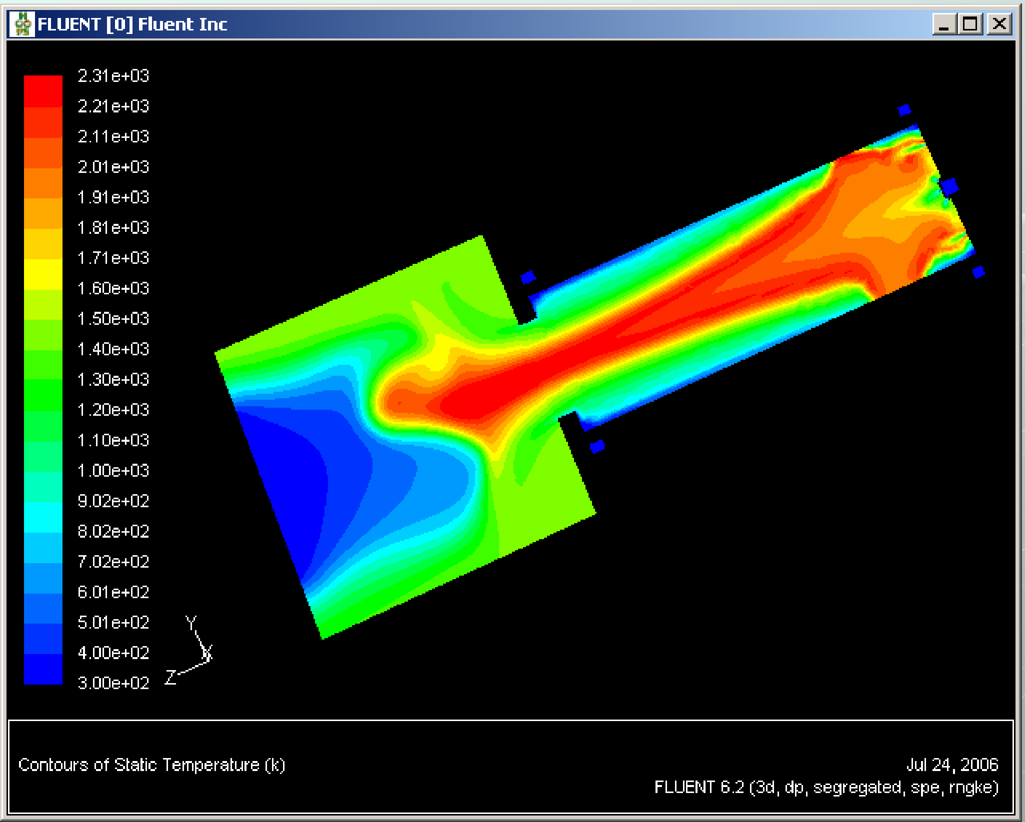
For all cases increase of air excess coefficient (α) causes decreasing of carbon monoxide concentrations along the combustor. Absolute CO values decrease for all air excess coefficients when spatial arc stabilization is turned on. Besides, the length of active CO formation zone is significantly reduced when chemical plasma influence is taken into consideration (see the next slide).

Results of the numerical experiments

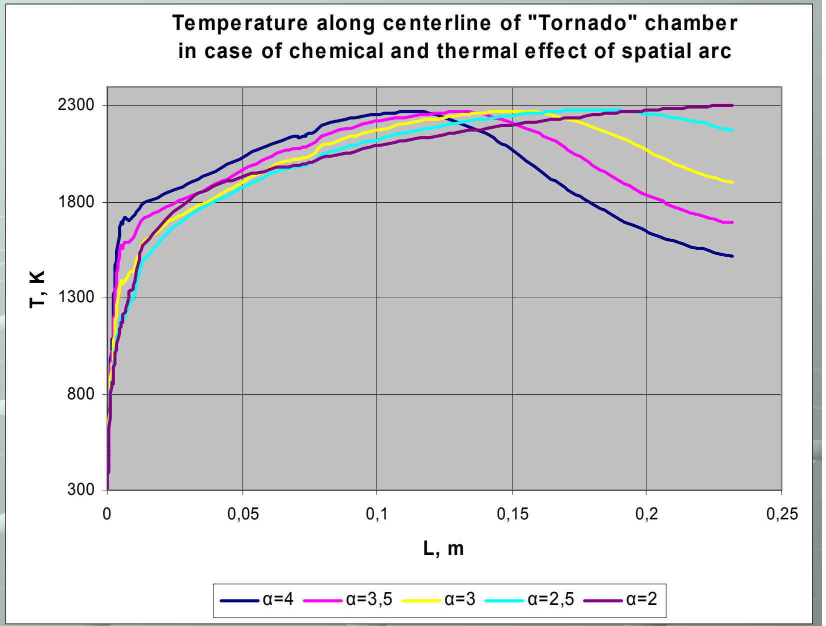


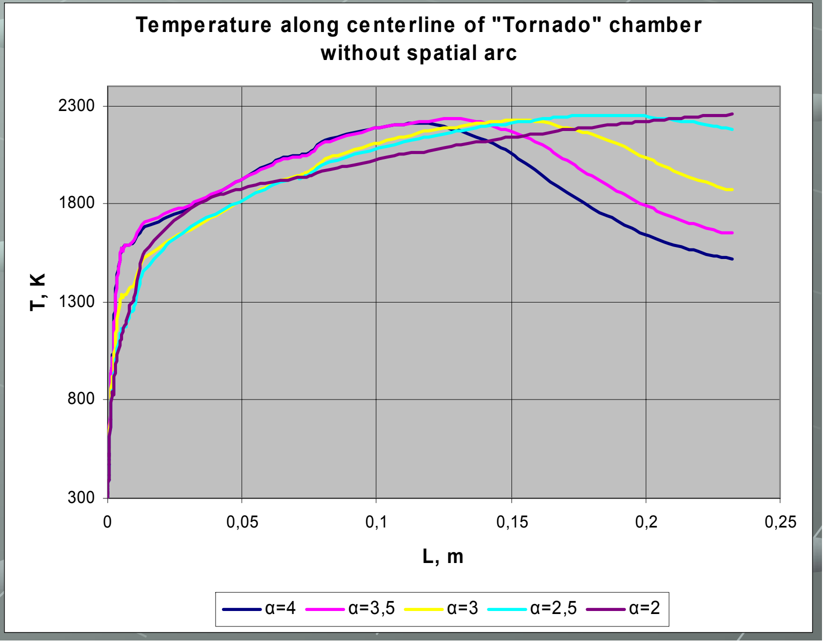


Results of the numerical experiments



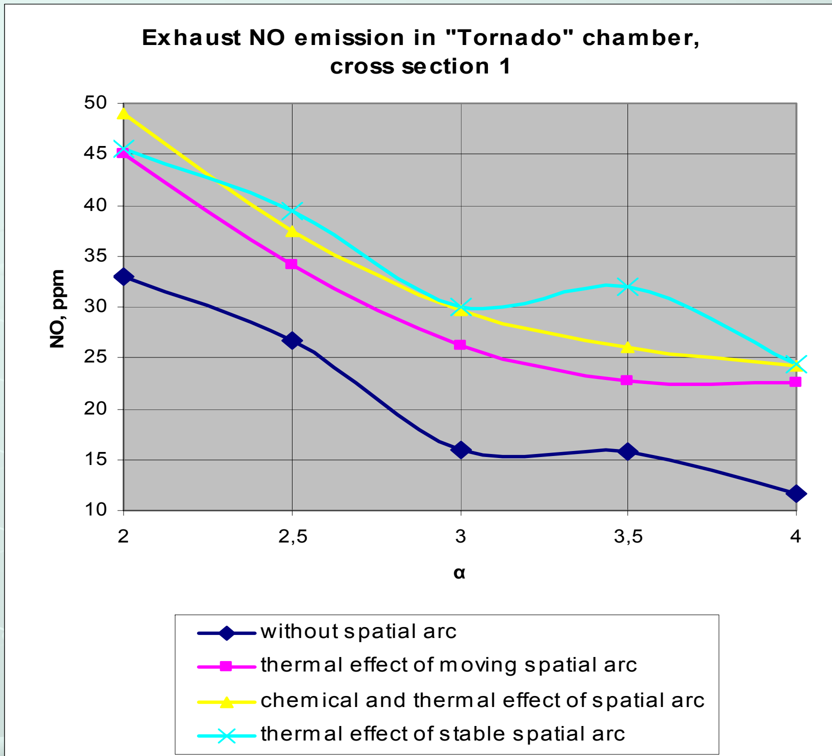
Temperature contours in “Tornado”-pilot

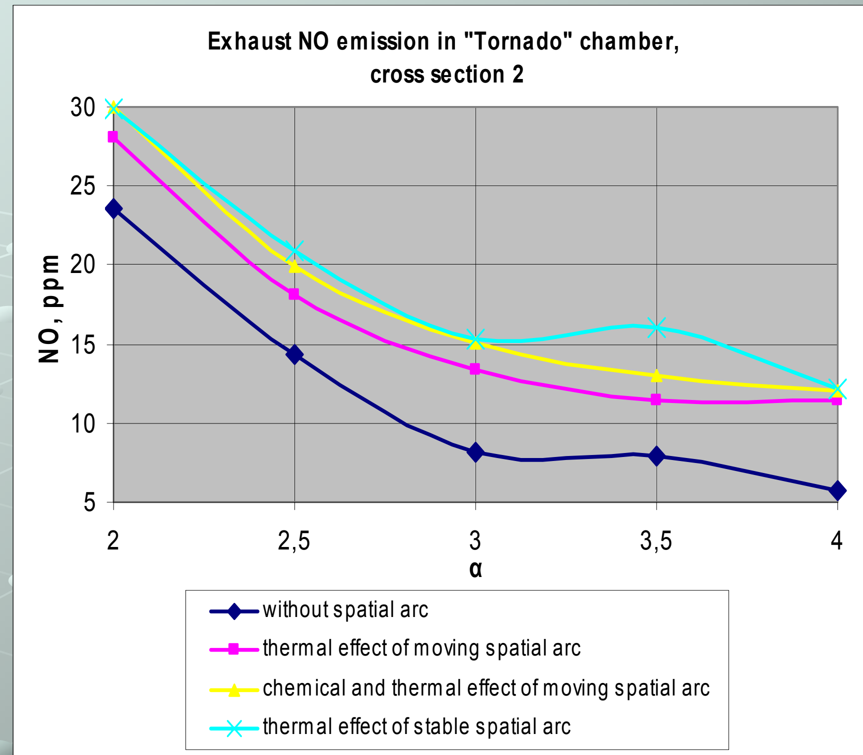




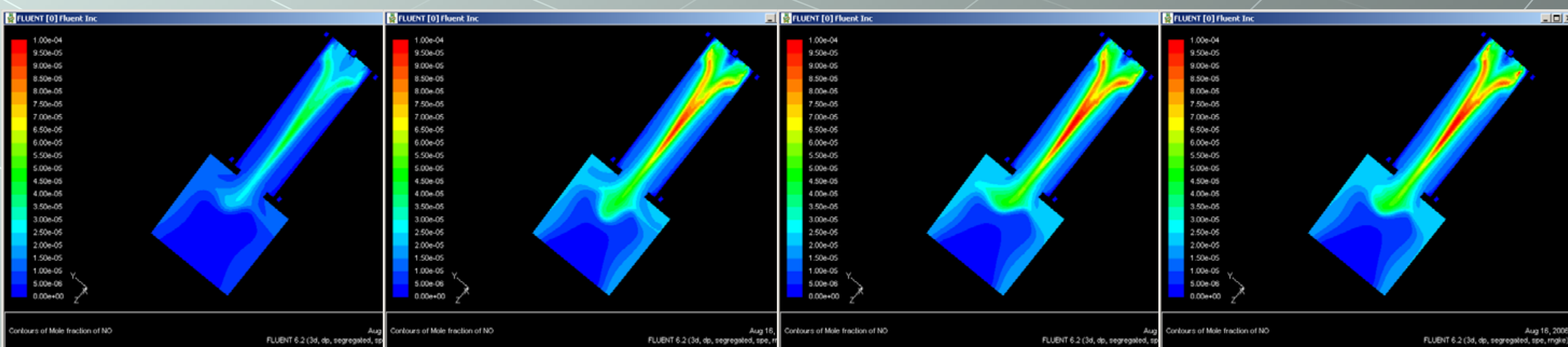
Spatial arc does not significantly change temperature distribution inside the combustor because the plasma, which is used for the burning intensification, is not thermal. The arc with power of 100 W increases temperature inside the chamber only by 20-30 degrees. The main reason for temperature field variation is the air excess coefficient changing. With increase of α flame length is decreased. It is shown in figures and diagrams.

Results of the numerical experiments

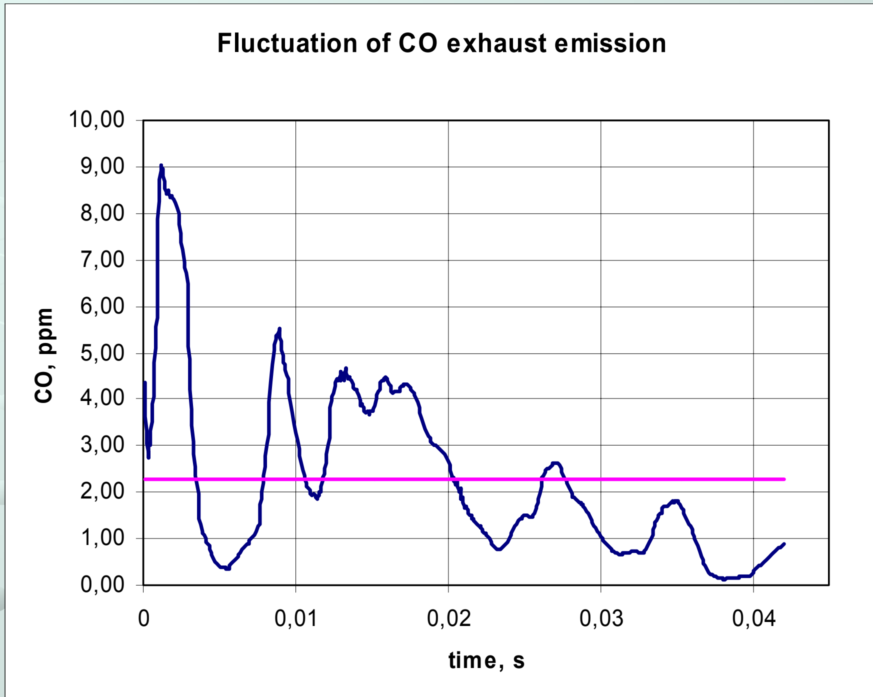


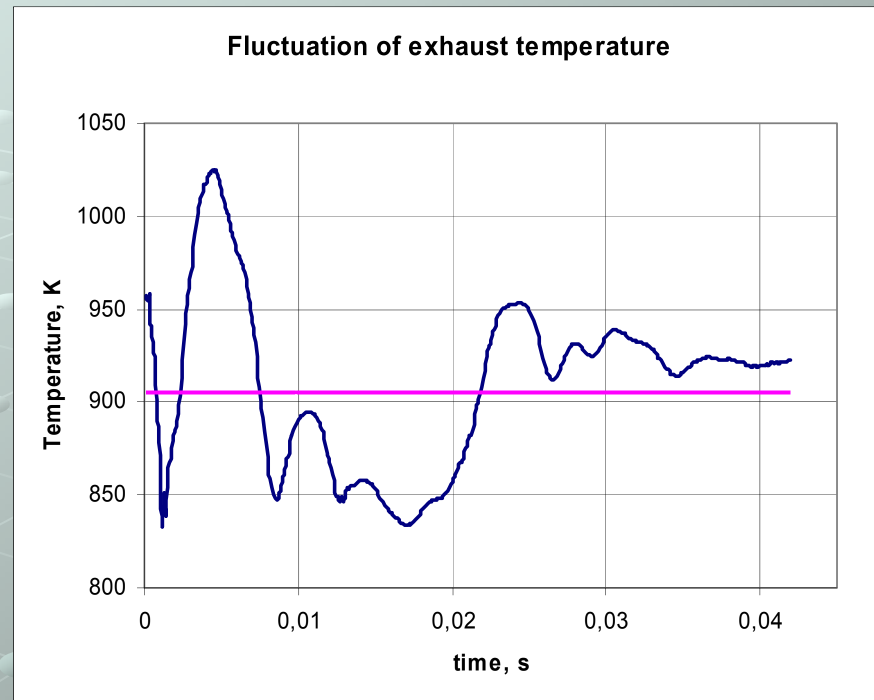


NO concentration field alfa=2



Results of the unsteady numerical experiments

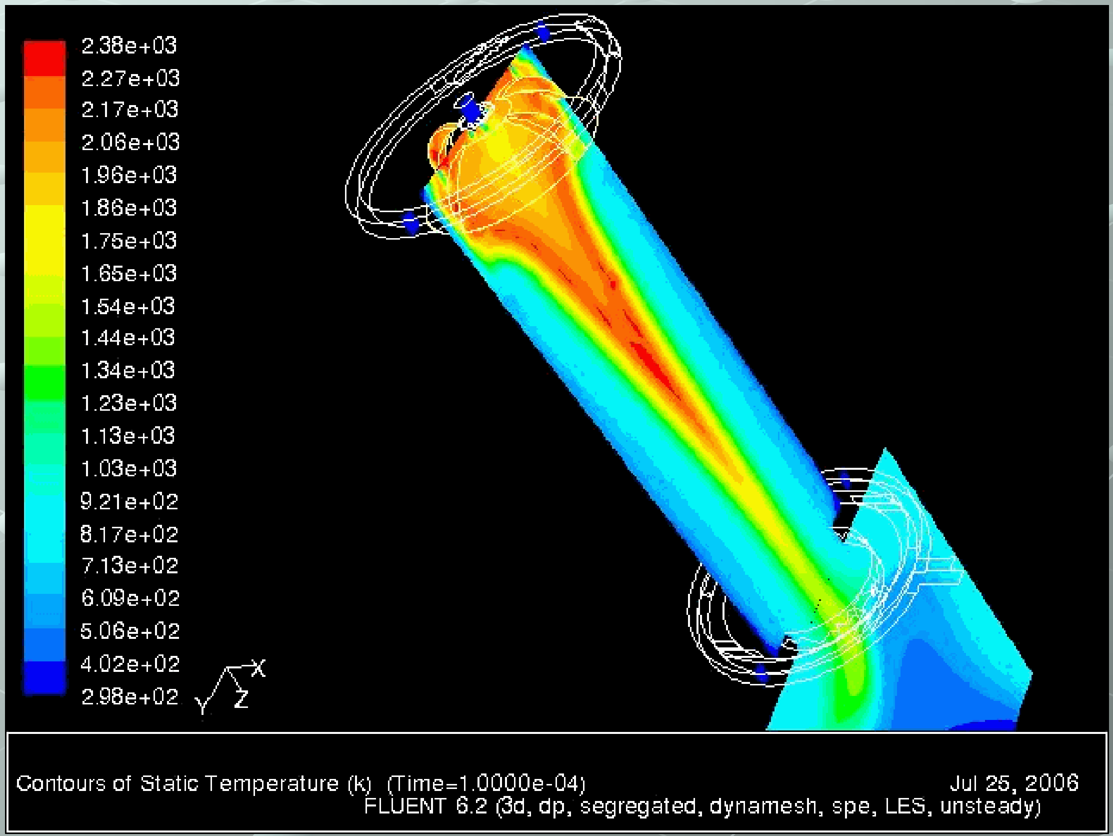




Unsteady combustor aerodynamic structure prediction with LES turbulence model is the next step of the numerical experiments. These calculations allow to find values of parameter fluctuations in the combustor that is necessary to insure burning process stability in the “Tornado”-pilot. The calculation time (0.042 s) was chosen to obtain a complete revolution of plasma arc. As LES-modeling requires additional computational resources and because lean mixtures are more unstable only case with air excess coefficient $\alpha = 4$ has been investigated. In figures time fluctuations of exhaust CO emission and temperature are shown. The large beginning parameter fluctuations are induced by discrepancies of initial conditions, but the numerical solution becomes more stable starting from 0.015 s, and fluctuations of all parameters decrease. The average values of exhaust temperature and CO emission are 905 K and 2.2 ppm accordingly.

Results of the unsteady numerical experiments

Temperature fields are changing in time. Flame structure is rather stable, but flame length is slightly shorter than in steady case. It should be noted the presence of the overheating zone in the combustor top.



Conclusions

- Theoretical investigations demonstrating the modeling opportunity for the complex aerodynamic flows in the “Tornado” combustor with spatial arc have been conducted
- Relations between air excess coefficients, NO and CO emissions, and exhaust temperature were determined both for cases with and without spatial arc
- Different factors of plasma effect such as thermal, chemical and mixing impact were analyzed separately
- The numerical analysis allowed to determine location of pollutant formation and overheating zones inside “Tornado” combustor
- Spatial arc application allows to decrease the CO emission on 50 % for all air excess coefficients in cross section 1 and on 36 % in cross section 2. The length of the active CO formation zone is reduced from 60 % for rich mixtures to 35 % for lean mixtures
- Obtained results and recommendations can be used for the reverse vortex combustor with spatial arc operational modes and geometry optimization, perspective combustors design and engineering for propulsion and power generation