Experimental and Numerical Definition of the Reverse Vortex Combustor Parameters

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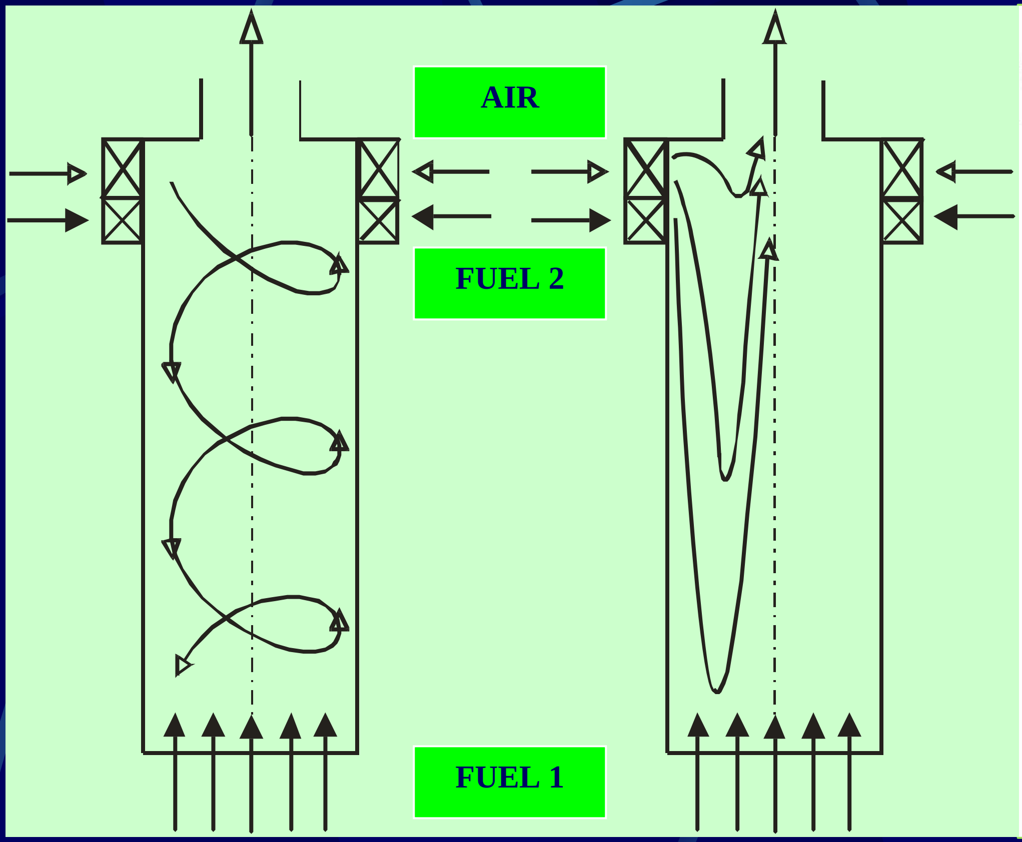
Objectives

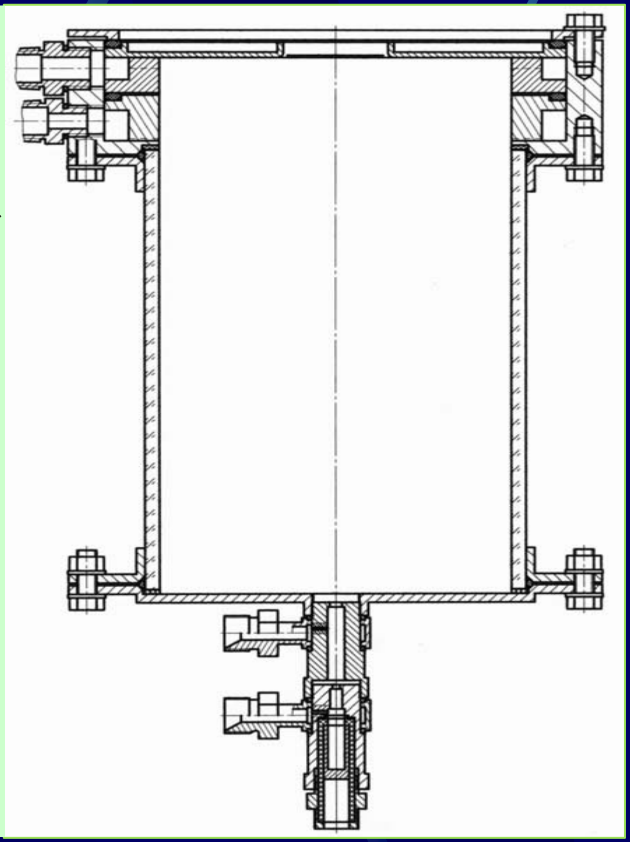
- **Develop a full-scale atmospheric pressure "Tornado Combustor" prototype based on innovative Reverse Vortex approach**
- **Start theoretical and experimental investigations of the working processes in the Tornado Combustor:**
  - **study the vortex behavior, including the low flow rate modes**
  - **determine efficiency of the walls thermal insulation**
  - **validate flammability limits**
  - **evaluate existing turbulence and combustion models and select the best ones for precise process description**

Contents

- The Combustor Aerodynamics, Design and Operational Parameters
- Thermal Isolation Efficiency
- Mathematical Modeling
- Preliminary Calculations
- Comparison with Visual and Measured Data
- Theoretical Investigations
- Conclusions
- Future Works

Aerodynamic Scheme and Combustor Design

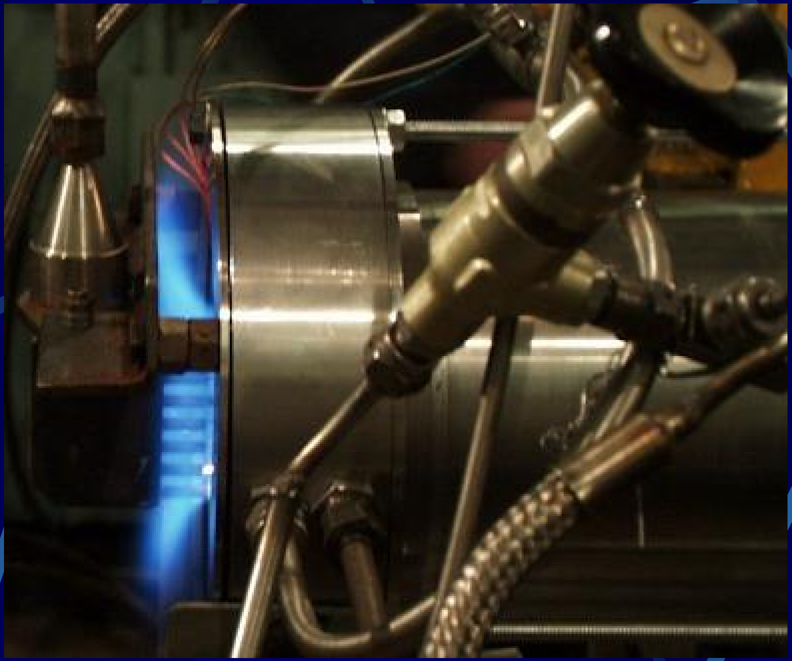




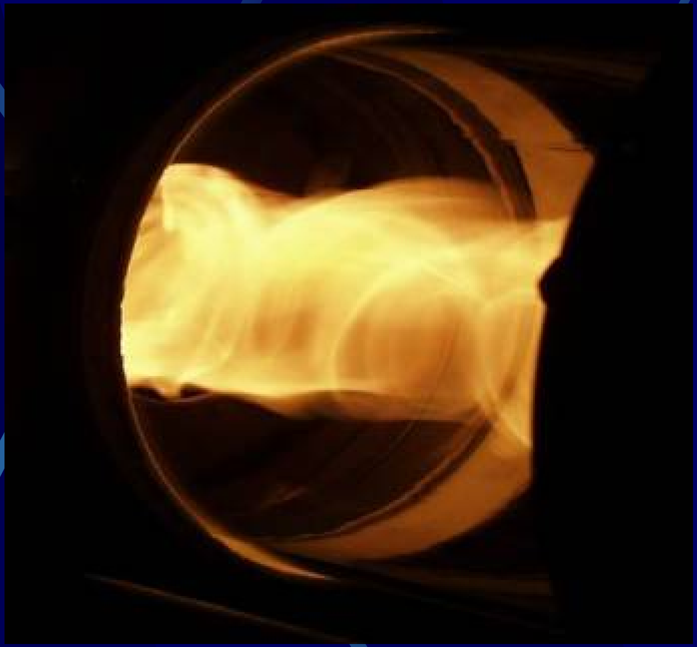
Aerodynamic scheme of the reverse vortex flow

Design of the atmospheric pressure Reverse Vortex Combustor

Operational Parameters



Reverse vortex combustor in operation

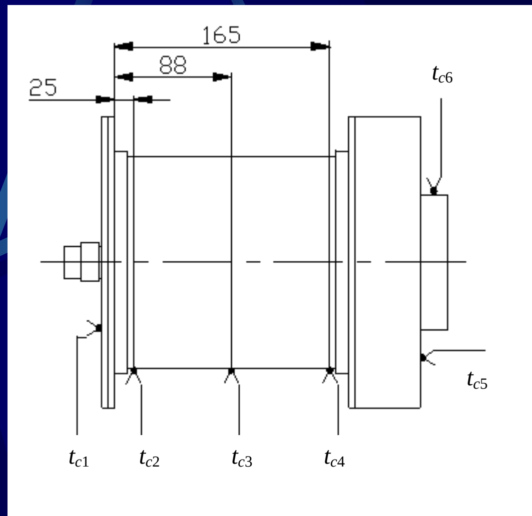


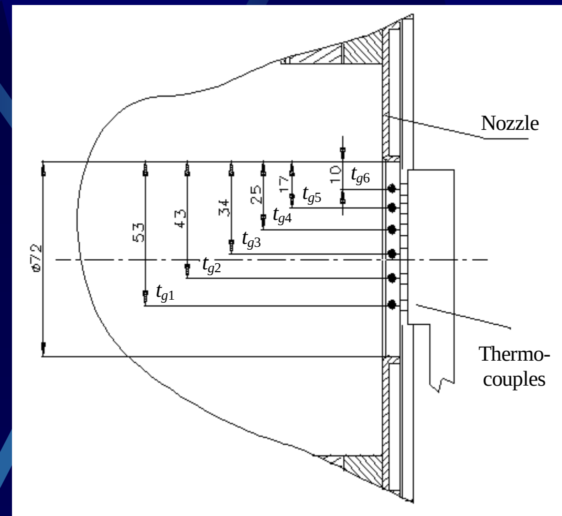
Visualization of the swirling reacting flow

The Combustor's Geometry and Operational Parameters:

- **Internal combustor dimensions: diameter 145 mm, length 240 mm**
- **Exhaust nozzle diameter - variable from 39 to 130 mm**
- **Fuel feeding: through two orifices on diameters 62, 92 and 124 mm or four tangential channels downstream the air input**
- **Air flow rate 0-20 g/s**
- **Fuel equivalence ratios 0.05-0.95**

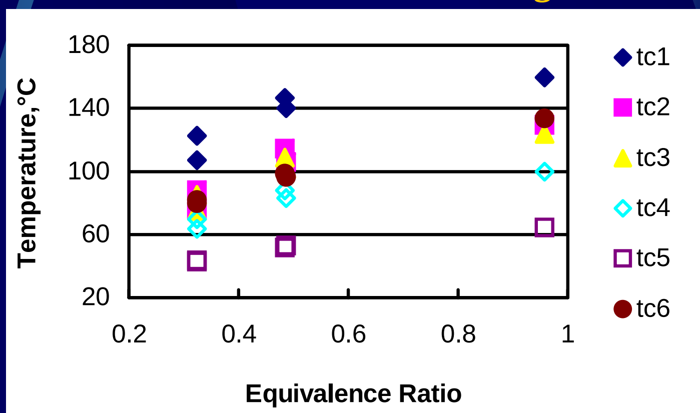
Thermal Insulation Efficiency



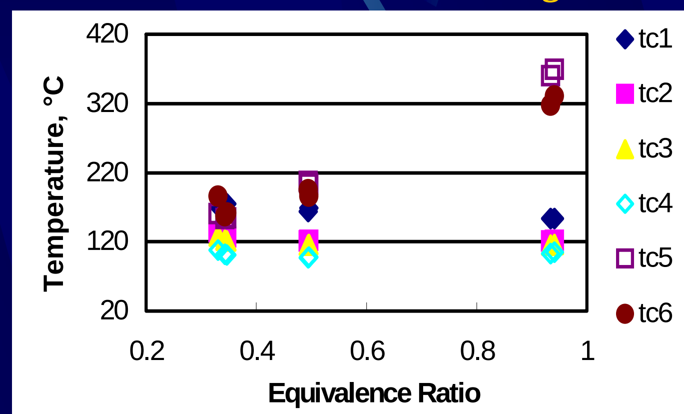


Scheme of the walls and exit temperature measurements in the RVC

Fuel flow rate 0.147–0.43 g/s



Fuel flow rate 0.226–1.007 g/s



Dependence of the walls temperature on the equivalence ratio

- **The maximum wall temperatures did not exceed 370 °C**

Mathematical Modeling

Mass conservation equation $\frac{\partial \rho}{\partial t}+\nabla\cdot(\rho u)=\dot{\rho}^{s}$, momentum conservation equation $\frac{\partial(\rho u)}{\partial t}+\nabla\cdot(\rho uu)=-\nabla p-\nabla\left(\frac{2}{3}\rho k\right)+\nabla\cdot\sigma+F^{s}+\rho g$,

continuity equation for species $\frac{\partial \rho_m}{\partial t}+\nabla\cdot(\rho_m u)=\nabla\cdot\left[\rho D\nabla\left(\frac{\rho_m}{\rho}\right)\right]+R_m+S_m$,

internal energy equation $\frac{\partial(\rho I)}{\partial t}+\nabla\cdot(\rho u I)=-\rho\nabla\cdot \mathrm{u}-\nabla\cdot J+\rho\varepsilon+\dot{Q}^{c}+\dot{Q}^{s}$,

turbulent kinetic energy transport equation $\frac{\partial \rho k}{\partial t}+\nabla\cdot(\rho u k)=-\frac{2}{3}\rho k\nabla\cdot \mathrm{u}+\frac{\sigma}{\nabla \mathrm{u}}++\nabla\cdot\left[\left(\frac{\mu}{\mathrm{Pr}_k}\right)\nabla k\right]-\rho\varepsilon+\dot{W}^{s}$,

dissipation rate of the turbulent kinetic energy transport equation

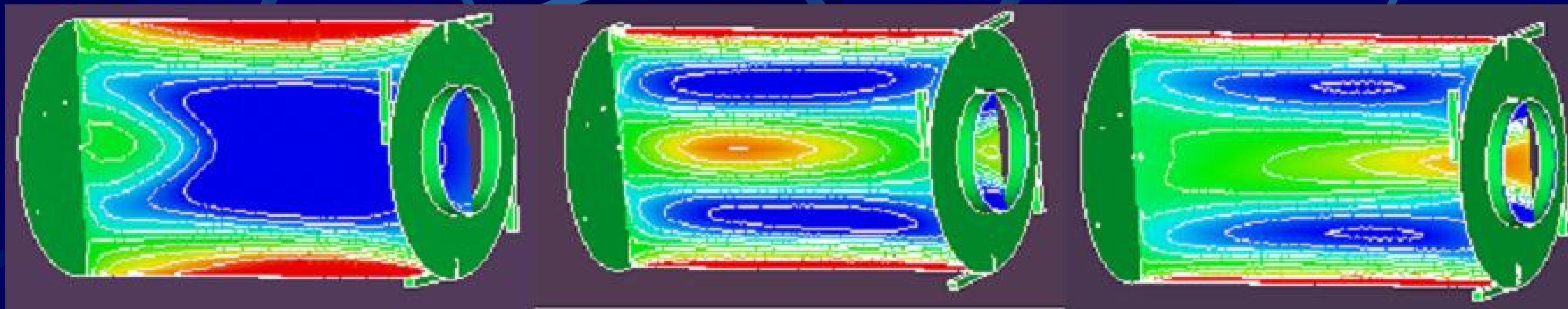
$$\frac{\partial \rho\varepsilon}{\partial t}+\nabla\cdot(\rho u\varepsilon)=-\left(\frac{2}{3}C_{\varepsilon_1}-C_{\varepsilon_3}\right)\rho\varepsilon\nabla\cdot \mathrm{u}+\nabla\cdot\left[\left(\frac{\mu}{\mathrm{Pr}_\varepsilon}\nabla\varepsilon\right)\right]+\frac{\varepsilon}{k}\left[C_{\varepsilon_1}\frac{\sigma}{\nabla u}-C_{\varepsilon_2}\rho\varepsilon+C_s\dot{W}^{s}\right].$$

$$\nabla=i\frac{\partial}{\partial x}+j\frac{\partial}{\partial y}+k\frac{\partial}{\partial z}, \qquad u=u(x,y,z,t)i+v(x,y,z,t)j+w(x,y,z,t)k,$$

source of chemical species $R_m=\sum_k R_{mk}$, $R_{mk}=\nu_{mk}M_m T^{\beta_k}A_k\prod_j\left[C_j\right]^{\nu'_{jk}}\exp(-E_k/RT)$, $R_{mk}=A\rho\frac{\varepsilon}{k}\frac{X_m}{\nu_{mk}}$,

Preliminary Calculations

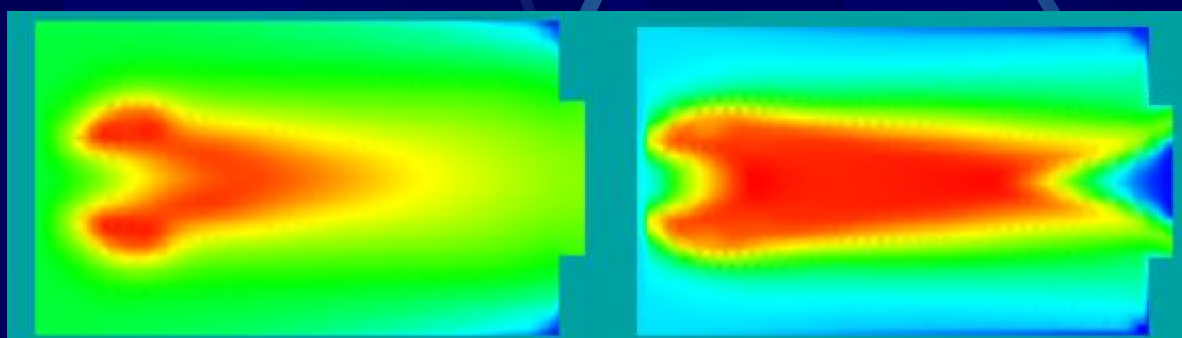
Air flow rate 12 g/s; maximum velocity +11 m/s; minimum – 7 m/s



k-ε turbulence model **RNG k-ε model** **RSM model**

Contours of cold flow axial velocity in 3D model of the reverse vortex combustor

Equivalence ratio 0.43; two fuel feeding holes on ID = 62 mm

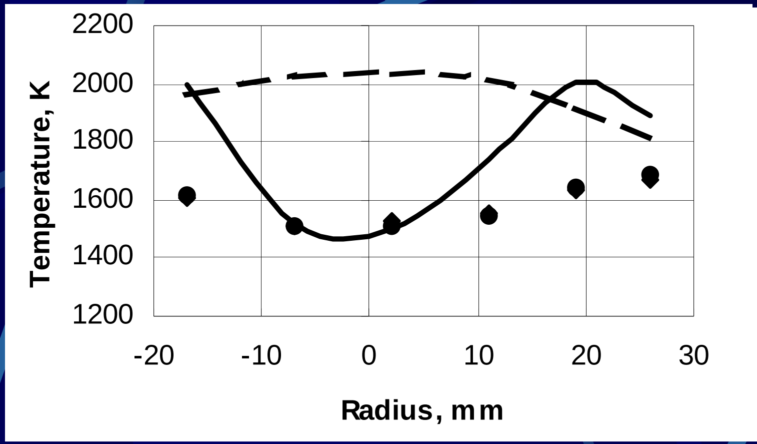


k-ε -model **RSM model**

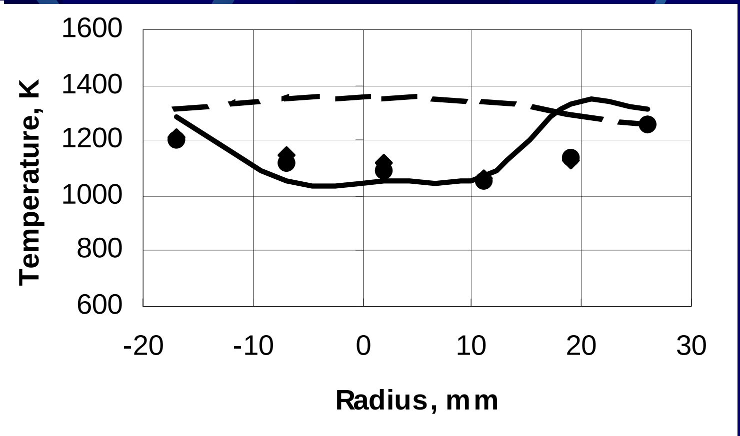
Contours of temperature in cross-section of the reverse vortex combustor

Radial Contours of Temperature

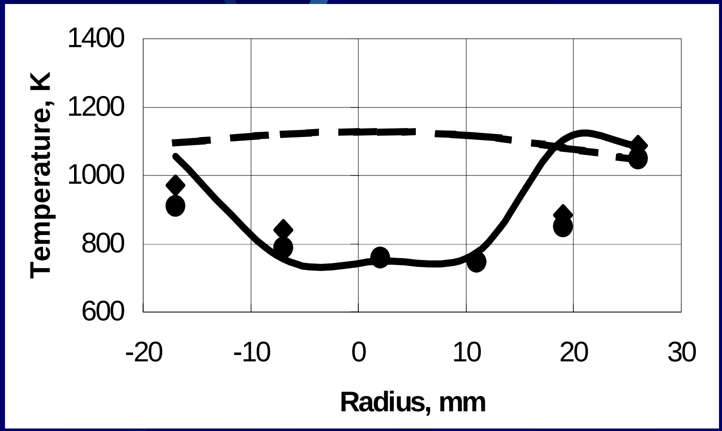
Equivalence ratio 0.67



Equivalence ratio 0.38



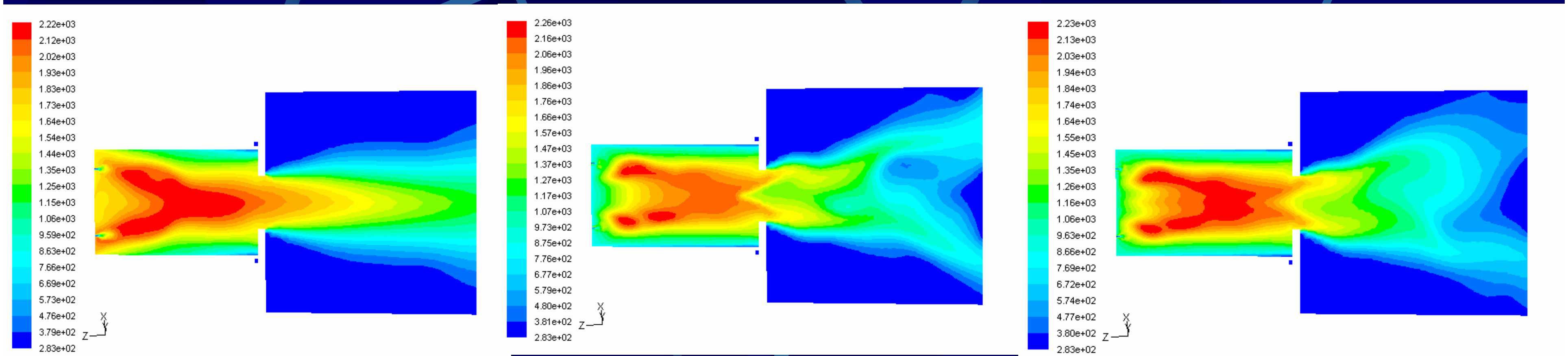
Equivalence ratio 0.29



Radial contours of temperature in the reverse vortex combustor exit:
——— RNG k-ε; – – – k-ε; ♦,● - experiment

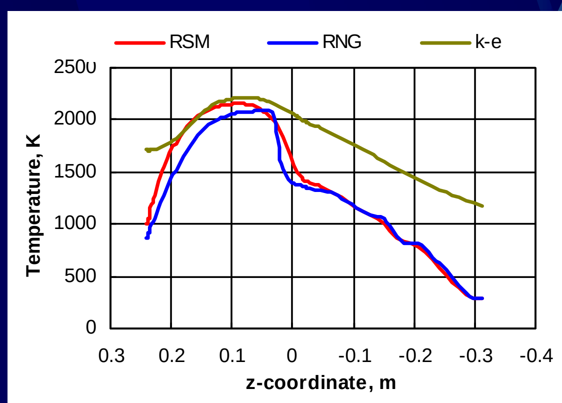
Theoretical Investigations

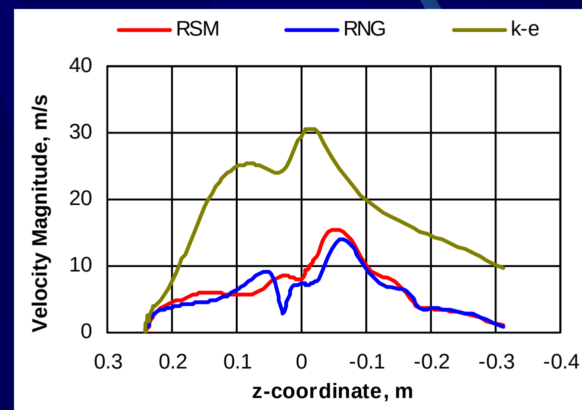
- ➢Air flow rate 14.41 g/s; gaseous fuel flow rate 0.695 g/s
- ➢Fuel feeding through two orifices on 92 mm diameter



k-ε model RNG k-ε model RSM model

Contours of static temperature in the RVC axial cross-section

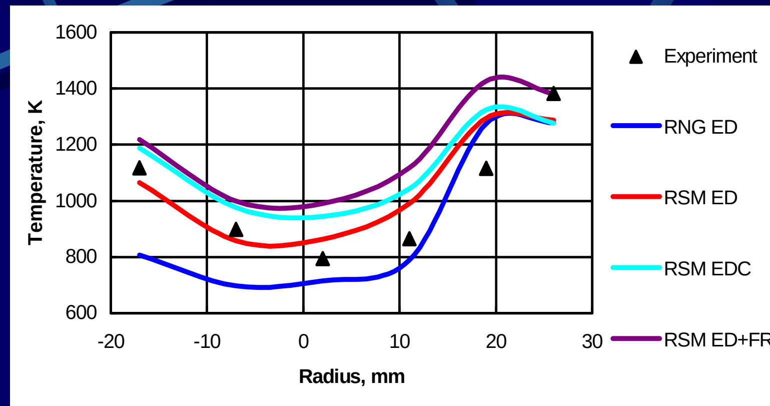




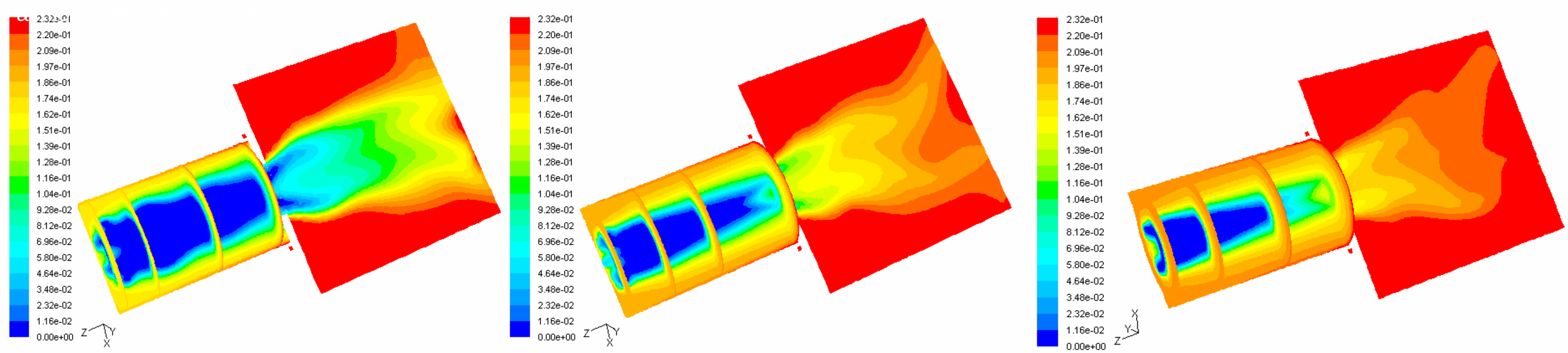
Dependences of temperature and velocity magnitude on the combustor length

Theoretical Results and Comparison with Experiments

Air flow rate 17.8 g/s



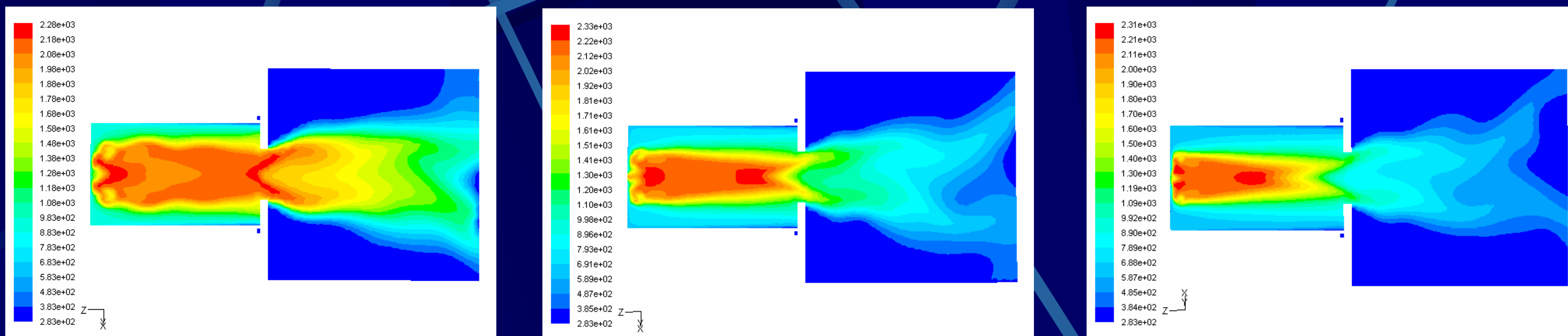
Radial contours of temperature in the reverse vortex combustor exit



ϕ = 0.935 ϕ = 0.495 ϕ = 0.349

Contours of mass fraction of oxygen in the RVC cross-section

Theoretical Results and Comparison with Visualization data

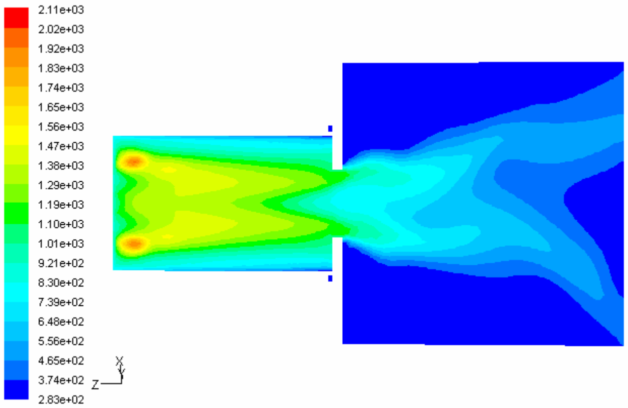


Contours of static temperature in the axial RVC cross-section

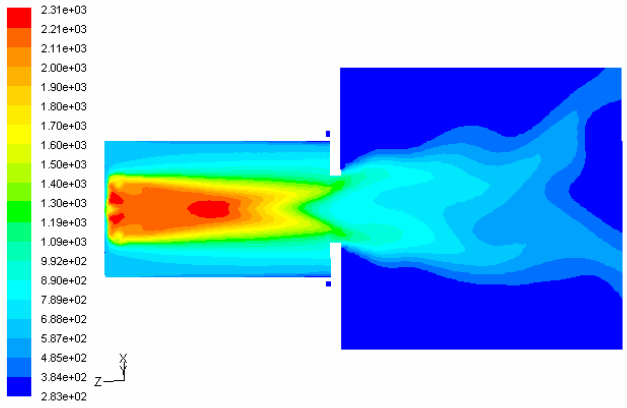
Visualization of the combustion processes in RVC

Theoretical Investigations

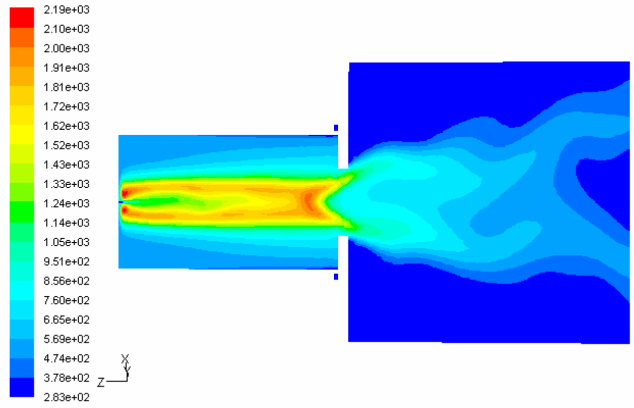
Air flow rate 17.56 g/s; fuel flow rate 0.366 g/s



124 mm fuel injection

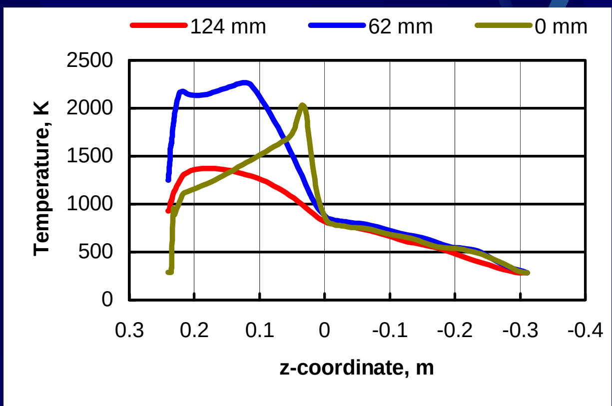


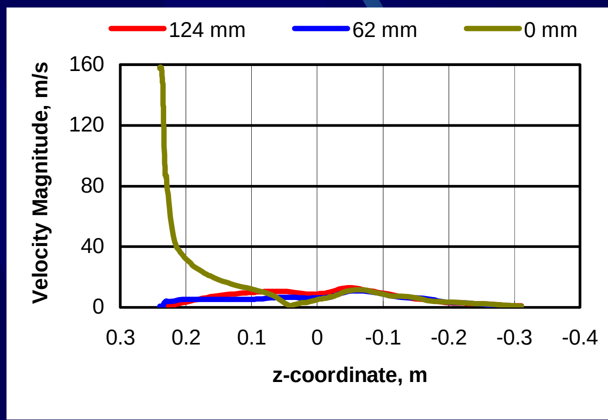
62 mm fuel injection



Central fuel injection

Contours of static temperature in the axial RVC cross-section

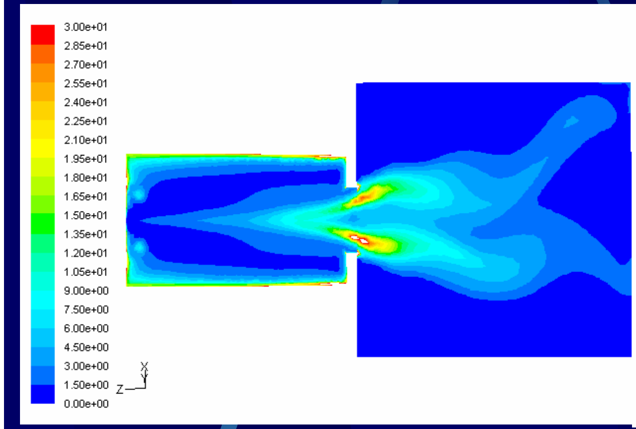




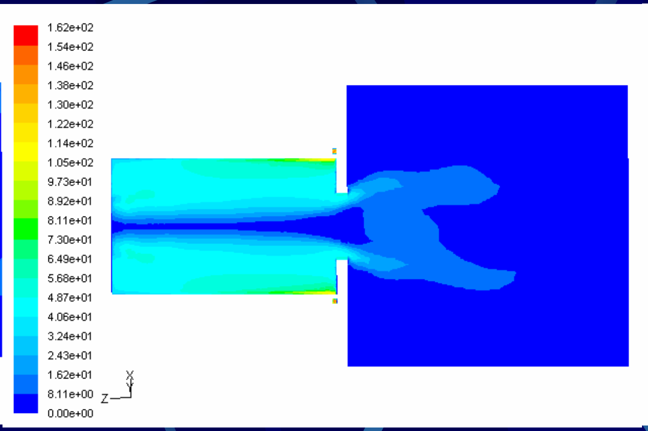
Dependences of temperature and velocity magnitude on the combustor length

Theoretical Investigations

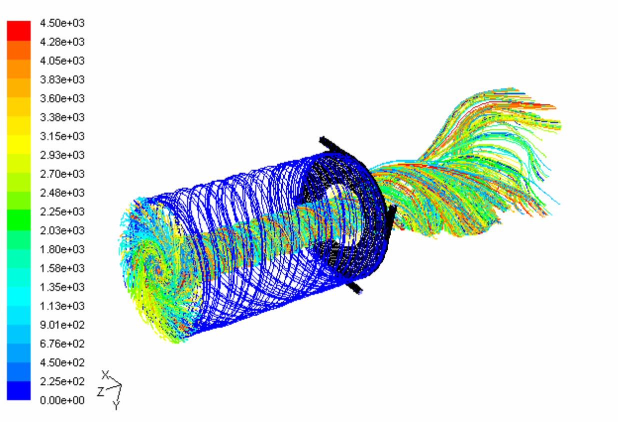
Air flow rate 17.56 g/s, fuel flow rate 0.366 g/s, 62 mm fuel injection, RSM turbulence model, Eddy-Dissipation combustion model



Contours of turbulence kinetic energy, m^2/s^2

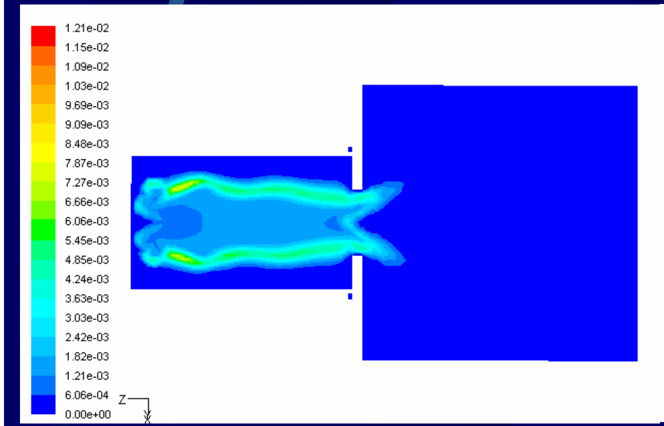


Contours of velocity magnitude, m/s

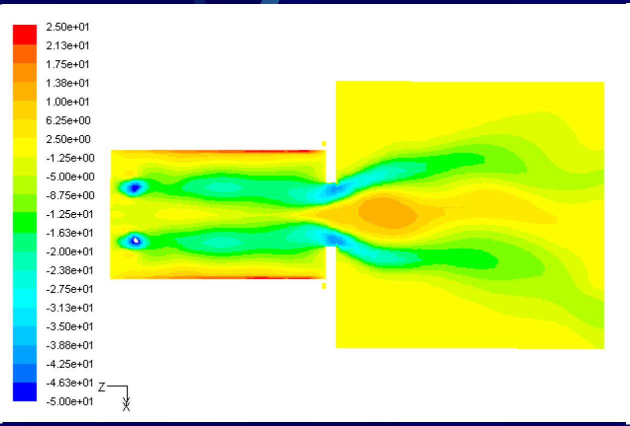


Path lines

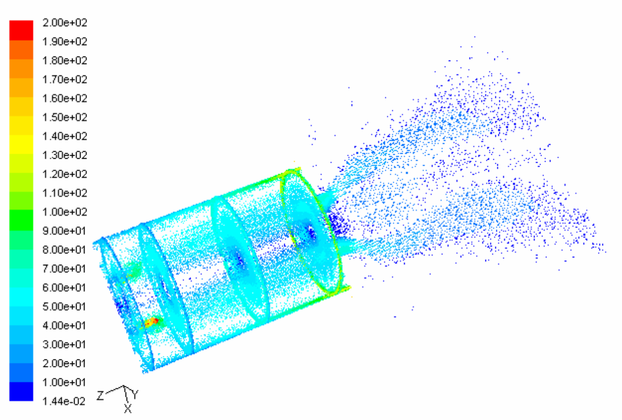
Air flow rate 17.8 g/s, fuel flow rate 1.007 g/s, 62 mm fuel injection, RSM turbulence model, Eddy-Dissipation combustion model



Contours of mass fraction of CO



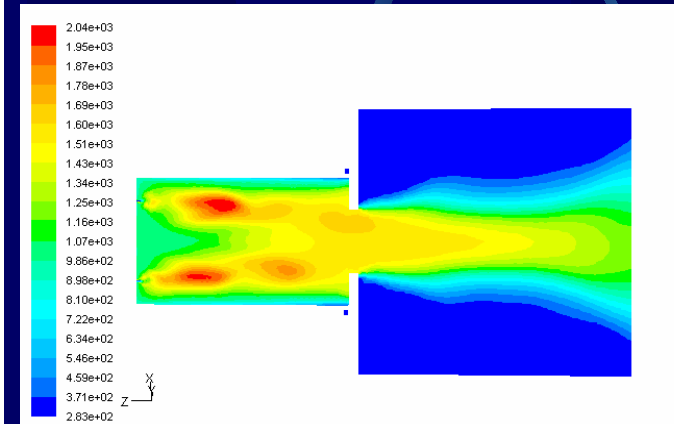
Contours of axial velocity, m/s



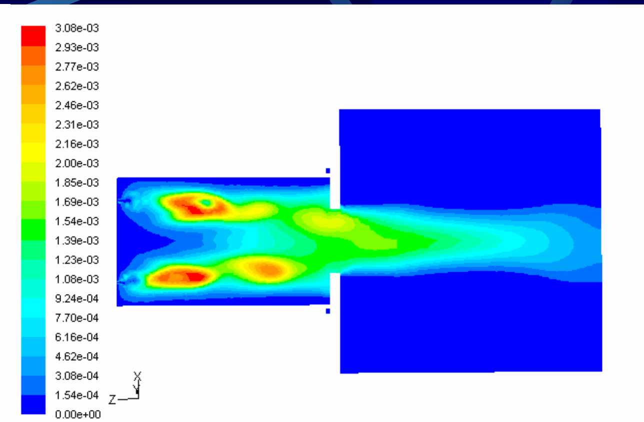
Velocity vectors, m/s

Theoretical Investigations

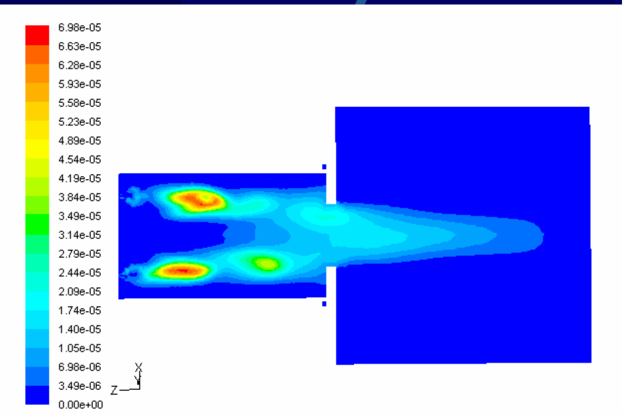
Air flow rate 17.41 g/s, fuel flow rate 0.695 g/s, 62 mm fuel injection, RSM turbulence model, PDF combustion model



Contours of static temperatures, K

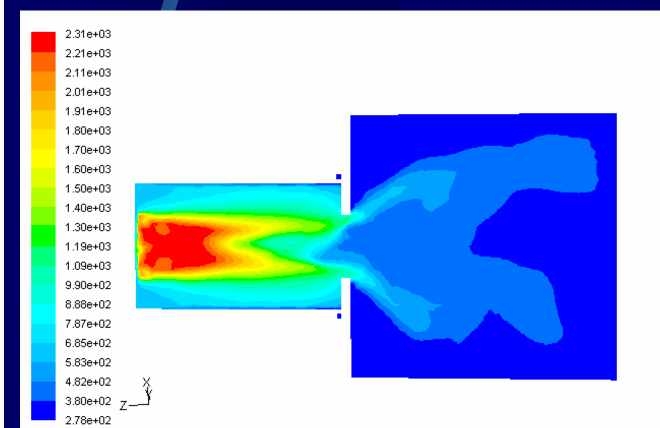


Contours of mass fraction of OH

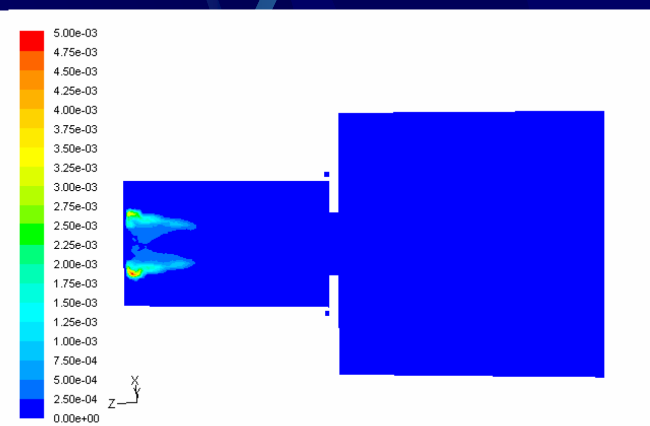


Contours of mass fraction of H

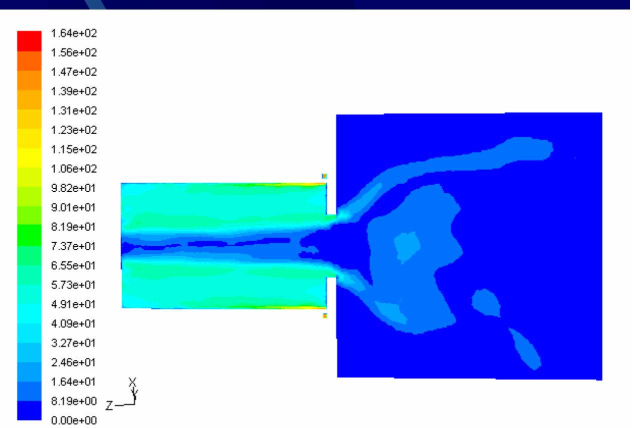
Air flow rate 17.56 g/s, fuel flow rate 0.366 g/s, 62 mm fuel injection, LES Smagorinsky-Lilly model, time 0.2251 s



Contours of static temperatures, K



Contours of mass fraction of CO



Contours of velocity magnitude, m/s

Summary

- New full-scale atmospheric pressure Tornado Combustor has been developed and preliminary tested on gaseous fuel
- Test results proved the “cold wall” concept, extremely wide flammability limits and unexpectedly low velocity to initiate the reverse vortex
- Conducted investigations revealed weak sides of the existing turbulence and combustion computation models for near stoichiometric mixture parameters prediction
- Obtained results and recommendations can be used for the reverse vortex combustor operational modes and geometry optimization, perspective combustors design and engineering for propulsion and power generation

Future Works

- Complete laser diagnostics of the reverse vortex flow in the developed full-scale Tornado Combustor
- Merge Tornado Combustor with Plasma Assisted Combustion System
- Optimize the fuel feeding system
- Improve selected turbulence model to increase the simulation accuracy
- Improve the combustor design based on calculated and measured data
- Conduct comprehensive validation tests of the improved Tornado Combustor with Plasma Assisted Combustion System

Acknowledgments

The authors would like to acknowledge Dr. Alexander Gutsol from Drexel University for his introduction into the reverse vortex flow investigations and Dr. Thomas A. Butcher, Brookhaven National Laboratory, for cooperation and valuable discussions of the flows structure computer modeling in isothermal and chemical reaction conditions. We would like also to thank personnel of the Zaporozhie Design Bureau “Progress” in Ukraine for hosting the combustor preliminary tests.