THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF A REVERSE-VORTEX PLASMA ASSISTED COMBUSTOR

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Theoretical and experimental investigations of the working processes in a reverse-vortex combustor with plasma pilot and spatial arc have been conducted. Selected concept of portable reverse-vortex plasma assisted combustor can provide higher performance, wider turn down ratios, more efficient propellants utilization, decrease combustor weight, demonstrate potential fuel flexibility, satisfy major gravimetric and volumetric density requirements. Obtained results and recommendations can be used for the reverse-vortex combustor operation modes and geometry optimization, prospective combustors for propulsion and power generation design and engineering.

INTRODUCTION

There are several major obstacles to overcome on the way of the perspective aircraft combustor development as: combustion efficiency, combustor's aerodynamic resistance, heightened sensibility of the working processes to inlet temperature and velocity irregularities, fuel/air ratio precise regulation, complicated design and high production cost, necessity in portable, lightweight and efficient subsystems as ignition, fuel feeding, flame control [1-3].

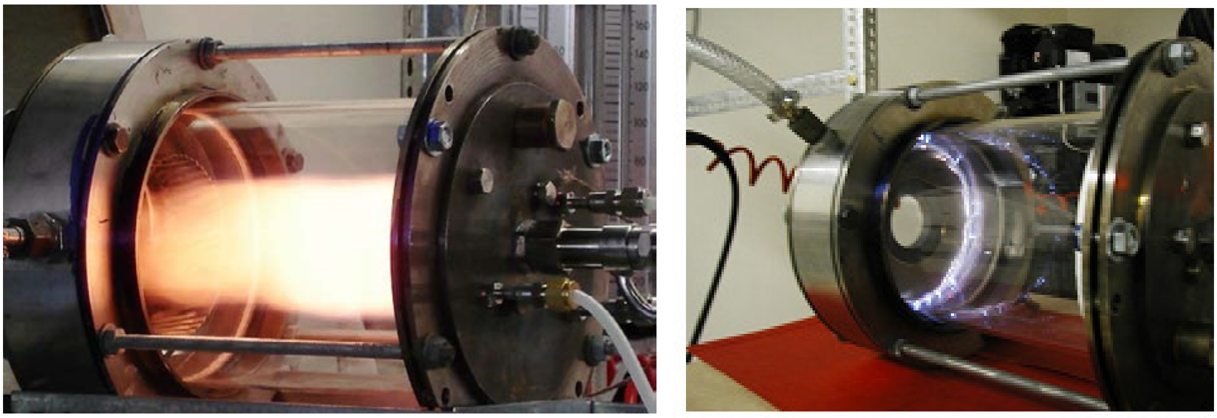
There is an opportunity to improve dramatically combustor's parameters by employing several innovations. They are as follows: 1) reverse-vortex flow, which provides cold walls and eliminates the compressed air need for their cooling, dramatically simplifies combustor design and swirlers, significantly widens flammability limits, provides more options for fuel selection [4-8]; 2) plasma arc (initiated inside a plasma pilot or inside a combustor in the form of spatial arc) for energy efficient and reliable ignition at any altitude and continuous flame control [4-7].

New generation of combustors development should be based on better understanding of the physical and chemical processes of turbulent combustion and ability of such combustors modeling taking in account complicity of their 3D geometry and variety of operation modes. A reverse-vortex plasma assisted combustor (RVPAC) has been developed and preliminary tested on the basis of the Applied Plasma Technologies (APT) patents and patent applications [4, 9, 10].

The main idea of the RVPAC stabilization is to establish a flame (or plasma jet) along the axis of a cylindrical combustion chamber in the opposite direction to incoming air, which is strongly swirling and flowing along the chamber walls. In this case, cold gas cannot move to the inner reverse flow zone before it loses the main part of its rotational speed. Hence, initially cold gas flows along the wall to the closed end of the cylindrical vessel, and turbulent micro-volumes of this cold gas, which have lost their kinetic energy near the wall, migrate radially towards the centre. As a result, cold gas comes into the hot zone from all sides, except the outlet side, and no significant recirculation zone is formed.

APT has an expertise in research and development of small scale reverse-vortex combustors for gas turbines and variety of portable plasma generators, plasma enhanced fuel reformers [7]. Recently engineered the basic reverse-vortex "Tornado" combustor with plasma pilot and spatial arc has been investigated. It has ID = 145 mm, length 240 mm, volume about 4 liters and was designed for atmospheric pressure operation and experiments with different fuels (liquid and gaseous) and reagents, as well as for fuel feeding solutions optimization. For the process visualization, the main wall could be fabricated from quartz. Preliminary combustor tests showed that the reverse vortex starts working at a very low pressure differential (about 50 mm of water column), which means low chamber resistance, as well as good protection of the chamber walls. Even with an output gases temperature of about 1200 °C, the walls and nozzle temperature did not exceed 340 °C. This means that no cooling is required. The reverse vortex mixes reagents very well; due to aerodynamics their residence time is much higher than in other vortex chambers, and the outlet nozzle could be up to 90 % of the chamber ID (from 45 to 130 mm). Working process visualizations in the RVPAC with plasma pilot (a) and spatial arc (b) are shown in Fig. 1.

Some CFD calculations have been done for better understanding of the reverse-vortex flow [6, 8, 11, 12]. Flow modeling using both the steady RNG k-ε-model and transient LES calculations gives qualitative conformity with the experimental data. Preliminary calculations have shown that with air velocity changing in tangential channels of the vortex generator from 40 up to 80 m/s (without special diffuser in reverse vortex combustor inlet) total pressure losses under fuel burning conditions come to 3.0-9.8 %. This value is comparable to pressure losses in the aircraft combustors equipped with diffuser for reduction of air velocity after compressor.



a) b)

Figure 1. Atmospheric pressure RVPAC with plasma pilot and spatial arc.

Previous engineering solutions [6] have essential imperfection consisting in generations of a spatial electric arc in the region of the combustor's exit nozzle. Therefore influence of non-equilibrium plasma on a high reaction fuel-air mixture formation in the combustor is considerably diminished. The spatial arc generation in the combustor's bottom region, where the hydrocarbon fuel is injected is fundamentally novel. That will demand the air flow partition on two streams: primary and plasma-forming, which enters the RVPAC through the own vortex generators. The complex flow structure in such a combustor requires detailed numerical simulation of reacting swirling streams interaction and corresponding experimental and theoretical investigations of the geometry and operation parameters.

REVERSE-VORTEX PLASMA ASSISTED COMBUSTOR

A hybrid type RVPAC ensures operation at two basic modes: with plasma pilot or with spatial arc. At the first stage of experiments the equipment check-out, approbation of sampling schemes, definition of stability operation range, and evaluation test of combustion system were carried out. Propane, injected into the plasma torch or spatial arc, was used as a hydrocarbon material. Additional vortex generator for air feeding has been installed in the bottom part of a reverse-vortex combustor with internal diameter of 73 mm and length of 150-300 mm (varied). The exhaust tube length and diameter were 100 and 50 mm correspondingly (Fig. 2).

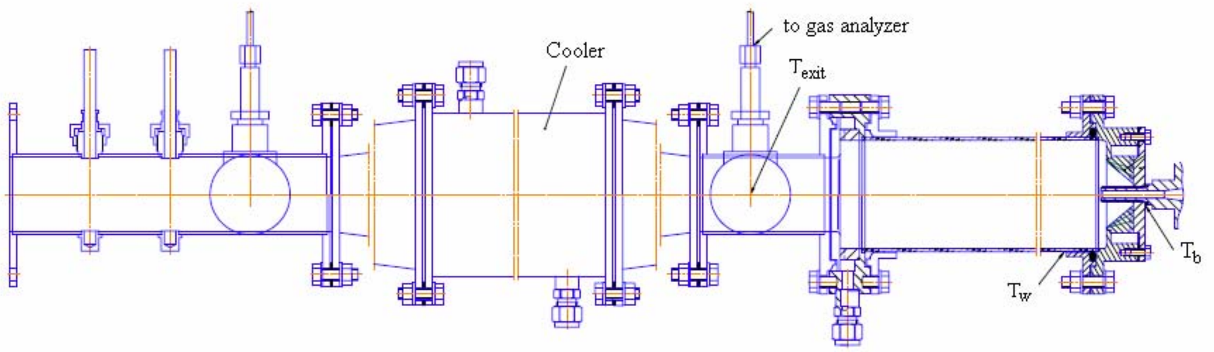


Figure 2. Plasma assisted combustion system with plasma pilot

Three different variants of the bottom swirlers (a) – (c) have been used (Fig. 3) with a plasma pilot. They have differed by a cone expansion angle, the conical part length, and length of the exit nozzle section.

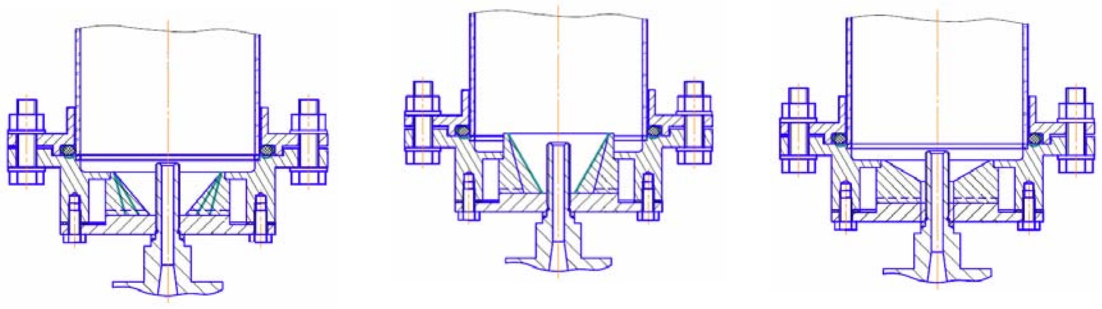


Figure 3. Different variants of the bottom swirlers.

Several prototypes of the continuously operating plasma pilots for land based and aerospace applications with arc power from 50 W to 1 kW, feedstock gas flow rate from 0.01 g/s to 3 g/s, plasma gas pressure differential from 20 mm H_2O to 6 m H_2O, and ambient temperature up to 600 °C have been recently developed and tested [5]. Variety of feedstock gases, including air, nitrogen, Ar, air + methane, and blends as air + propane, air + hydrogen can be applied without any soot formation inside the arc chamber. One of the plasma pilot prototypes is shown in Fig. 4.

Figure 4. Plasma pilot with fuel injection in operation.

For the purpose of immediate effect of non-equilibrium plasma on the processes of combustion-mixture preparation a small-sized RVPAC with internal diameter 73 mm and length 150 mm was designed and manufactured (Fig. 5). For this design a spatial arc initiation occurs in the bottom area. Primary and plasma feedstock air are injected separately through the tangential channels of the vortex generators located near the exit nozzle and the bottom part accordingly. In this case excitation of a rotating spatial arc in a fuel feeding zone ensures conditions for thermal, kinetic and turbulent influence of plasma discharge on the processes of mixing, ignition and burning.

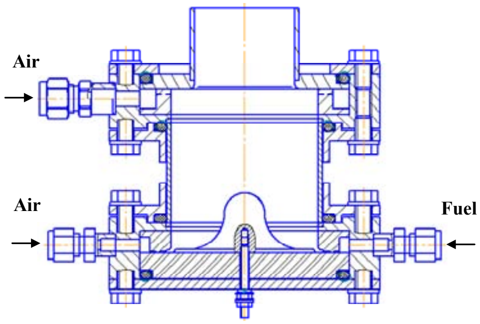


Figure 5. Plasma assisted combustor with spatial arc.

Excitation of the spatial arc was provided by a custom designed high-voltage (up to 30 кV) power supply having a capability for power control from 10 to 200 W. Because of low power arc, no visible erosion of electrodes was observed (central cathode and casing) even after several hours of operation.

In experiment the following modes of the gaseous fuel injection into the reverse-vortex plasma assisted combustor were provided: a) together with plasma feedstock air; b) through a plasma pilot installed at the bottom plate centre; c) by a central atomizer; d) through four symmetrically located nozzles.

EXPERIMENTAL INVESTIGATIONS

In Fig. 6 temperatures of the bottom part (T_b), cylindrical wall (T_w) of the RVPAC with plasma pilot (Fig. 2), and also NO_x and CO exit concentrations as the functions of total air excess coefficient λ are shown. During conducted tests plasma feedstock air flow rate was kept constant and equal to 0.514 g/s, main (ensuring a reverse stream) air flow rate varied from 6.59 to 28.59 g/s, air flow rate through the bottom vortex generator varied from 0 to 5.23 g/s, and propane consumption changed from 0.085 to 0.48 g/s.

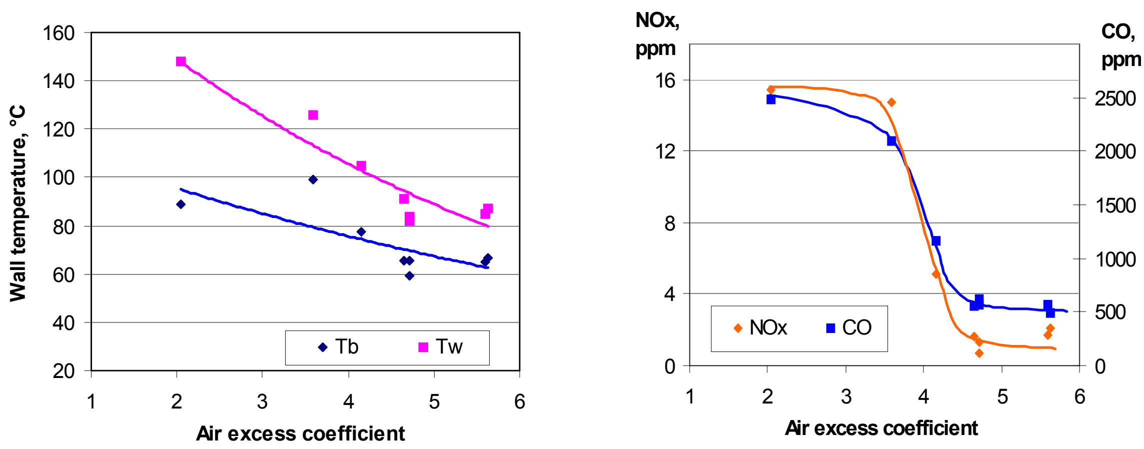


Figure 6. Wall temperatures, NO_x and CO concentrations as functions of total air excess coefficient.

In all experiments with propane combustion the power, consumed by a plasma device, did not exceeded 100 W at electric current 80-100 mA. Maximum wall temperatures did not exceeded 90 and 150 °C at the air excess coefficients λ equal 5.59 and 2.04 correspondingly, which confirms a combustion system cooling effectiveness and possibility of low-cost materials application.

Level of nitrogen oxides emission at the combustion system exit measured by TESTO-350 XL gas analyzer was pretty low. For the air excess coefficient λ = 2.04 it was equal to 15.4 ppm, for λ = 5.59 diminished to 1.7 ppm and even lower. Since experiments were held at near atmospheric pressure conditions inside the combustor, CO emission level was pretty high - 572 ppm with air excess coefficient λ = 5.59. This fact leads to necessity to optimize the combustor's geometry, improve mixing processes and optionally in some cases utilize the catalytic neutralization method to reduce unburned CO.

On the next stage of conducted tests an influence of steam injection into the RVPAC with plasma pilot was investigated. In this case a bottom air swirler was replaced by a steam feeder. In Fig. 7 the wall (T_b, T_w) and exit temperatures T_{exit}, NO_x and CO concentration as the functions of steam flow rate are presented.

During the tests the certain parameters were hold constants: plasma feedstock air flow rate 0.443 g/s, main air flow rate 7.156 g/s, propane consumption 0.34 g/s. These parameters correspond to total air excess coefficient λ = 1.47. Steam flow rate varied from 0 to 1.07 g/s, power consumed by the plasma torch, was about 56 W at electric current 45 mA. It was mentioned that increase of a steam flow rate reduces the combustor's wall and exit temperatures, and also decreases nitrogen oxide emissions. For operation modes with near-stoichiometric air excess coefficient a steam injection results in some reduction of CO emission at the combustor exit, while in lean mixtures a steam feeding slightly augments the CO concentrations.

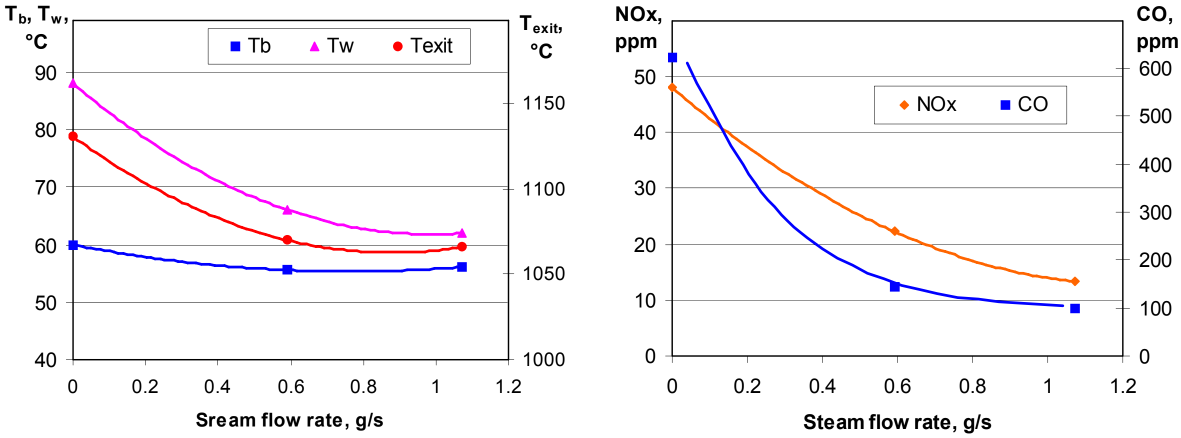
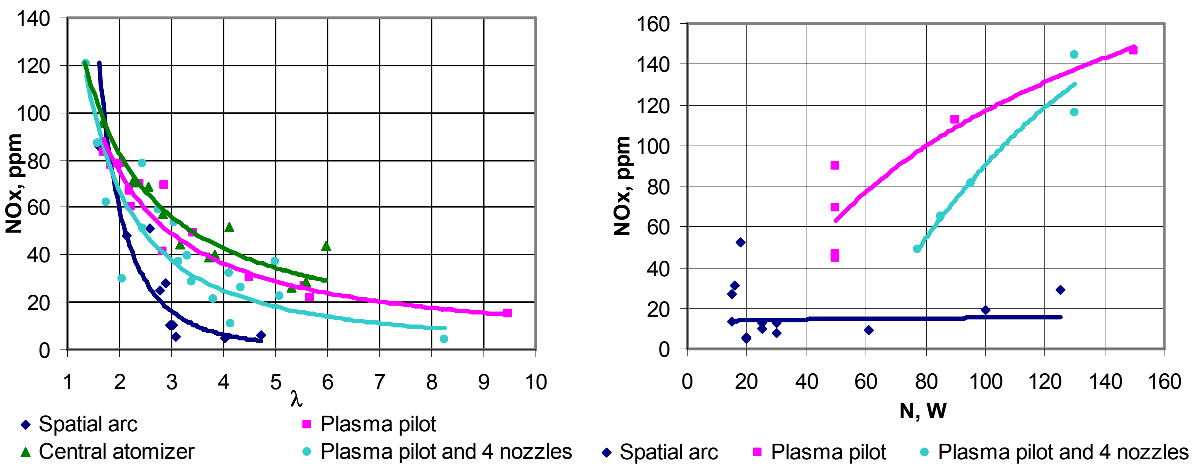


Figure 7. The wall and exit temperatures, NO_x and CO concentrations as the functions of a steam flow rate.

Figure 8 shows generalized dependences of a nitrogen oxide emission on the combustor operation modes characterized by the air excess coefficient λ for four basic fuel injection methods without electric discharge initiation (Fig. 8,a), and with plasma device (plasma pilot and spatial arc) operation (Fig. 8,b). NO_x emission did not exceed 150 ppm for λ varying from 1.5 to 9.5 and the tendency for its increase occurs with the discharge power growth.



a) b)

Figure 8. NOx concentration at the RVPAC exit.

TREORETICAL INVESTIGATIONS

A number of numerical simulations for the RVPAC were made to investigate the influence of electric arc on chemical processes inside the combustor. Interaction of the vortex flows of primary and plasma feedstock air (spreading along the cylindrical wall) causes very complicated aerodynamic flow structure inside the combustor. In the 3D CFD-calculations the RNG k-ε-model of turbulence, multistage reactions of propane burning, segregated solver, steady formulation, pressure-velocity coupling are used with taking into consideration influence of the turbulent pulsations on kinetics within the framework of Eddy Dissipation Concept.

For modeling of physical and chemical processes inside the RVPAC with plasma pilot and 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. This method provides a procedure of the sequential numerical integration of the differential equations, which describe reacting viscous gas flows. Modeling of physical and chemical processes in the reverse-vortex combustor is based on solution of the well-known system of the differential equations of mass, impulse and energy conservation for the multi-component, turbulent, chemically reacting system [6, 11, 12-16] in the following way:

- the mass conservation equation

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

- the momentum conservation equation

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

- the continuity equation for species

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla(\rho \vec{\upsilon} Y_i) = -\nabla \cdot \vec{J}_i + R_i + S_i,$$

- the internal energy equation

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

- the turbulent kinetic energy transport equation

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

- the dissipation rate of the turbulent kinetic energy transport equation

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

$$\mu_{t0} = C_\mu \rho k^2 / \varepsilon, \ \mu_t = \mu_{t0} f(\alpha_s, \Omega, \frac{k}{\varepsilon}), \ R_\varepsilon = \frac{C_\mu \rho \eta^3 (1 - \eta / \eta_0)}{1 + \beta \eta^3} \frac{\varepsilon^2}{k}, \ \eta = Sk / \varepsilon.$$

In these equations *t* is time; ρ is a mass density of mixture; S_m is the mass added to the continuous phase from the dispersed second phase and any user-defined sources; *p* is a fluid pressure; τ_{st} is the stress tensor; $\rho \vec{g}$ and $\vec{F}$ are the gravitational body force and external body forces; Y_i, R_i are the mass fraction and net rate of production of species i by chemical reaction; $\vec{J}_i$ is the diffusion flux of species i; S_i is the rate of creation by addition from the dispersed phase plus any another sources; S_h is the heat of chemical reaction and any other volumetric heat sources; *k* and ε are the turbulent kinetic energy and the rate of its dissipation; μ_{eff} is the effective viscosity; G_k represents generation of a turbulence kinetic energy due to the mean velocity gradients; G_b is the generation of turbulence kinetic energy due to buoyancy; Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate; the quantities α_k and α_ε are the inverse effective Prandtl numbers for *k* and ε, respectively; S_k and S_ε are user-defined source terms; $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$ are the constants of turbulence model; μ_{t0} is the value of turbulent viscosity calculated without the swirl modification; Ω is the characteristic swirl number; α_s is the swirl constant.

We have to note, that in circulating flows turbulence viscosity factor is anisotropic. That's why application of a standard *k*–ε- turbulence model could be not efficient. For those cases the RNG k–ε-model could be applied. The RNG-based *k*–ε- turbulence model is derived from the instantaneous Navier-Stokes equations, using a mathematical technique called "renormalization group" (RNG) methods [16].

The Eddy Dissipation Concept combustion model assumes that reaction occurs in the small turbulent structures, called fine scales. Species react in the fine structures over a timescale. Reactions proceed over the time scale, governed by Arrhenius rates and are integrated numerically using ISAT algorithm. So to calculate the net source of species *i* by chemical reaction it is necessary to find the volume fine scale and time scale.

The length fraction and time scales are

$$\xi^* = C_\xi \left(\frac{\nu\varepsilon}{k}\right)^{3/4}, \quad C_\xi = 2{,}1377; \qquad \tau^* = C_\tau \left(\frac{\nu}{\varepsilon}\right)^{1/2}, \quad C_\tau = 0{,}4082.$$

The net source of species *i* by chemical reaction

$$R_i = \frac{\rho(\xi^*)^2}{\tau^*[1-(\xi^*)^3]}(Y_i^* - Y_i).$$

The boundary conditions in the axial and radial inlets, symmetry axes, walls and outlet from the RVPAC were set in accordance with the conditions for carrying out physical experiments and recommendations for modeling the turbulent burning processes. The method for the system solution, the finite difference scheme and the solution stability analysis are explained in detail in [12-16].

For comparison of theoretical and experimental data numerical simulations of the RVPAC with plasma pilot located at the bottom combustor part are carried out. Operation conditions for combustor test are the following: air mass flow rate through the tangential swirler 15.53 g/s, air inlet temperature 318.5 K, air mass flow rate through the plasma pilot 0.666 g/s, temperature of plasma feedstock air 294.1 K, propane mass flow rate through the plasma pilot 0.155 g/s, propane inlet temperature 294.1 K. During CFD calculations the RNG *k-ε* turbulence model with a swirl dominated flow, 3D pressure based solver, steady formulation, SIMPLE pressure-velocity coupling, EDC combustion model of propane (C_3H_8) are used.

Figure 9 shows the scheme of working fluids injection and the static temperature distribution in combustor volume. Note, that gaseous propane was injected into plasma pilot channel together with plasma feedstock air**.** Therefore their preliminary mixing has been ensured. Figure 9 shows also comparison of the actual (squares and triangles) and predicted (blue and green lines) radial gas temperature contours in two cross-sections of combustor exhaust tube (distance 102 and 205 mm from exit nozzle). Actual temperatures have been measured simultaneously by five thermocouples located on different radiuses. Satisfactory conformity of experimental and calculated data testifies about adequacy of proposed mathematical model and about capability of its further using for parameters optimization of the RVPAC system.

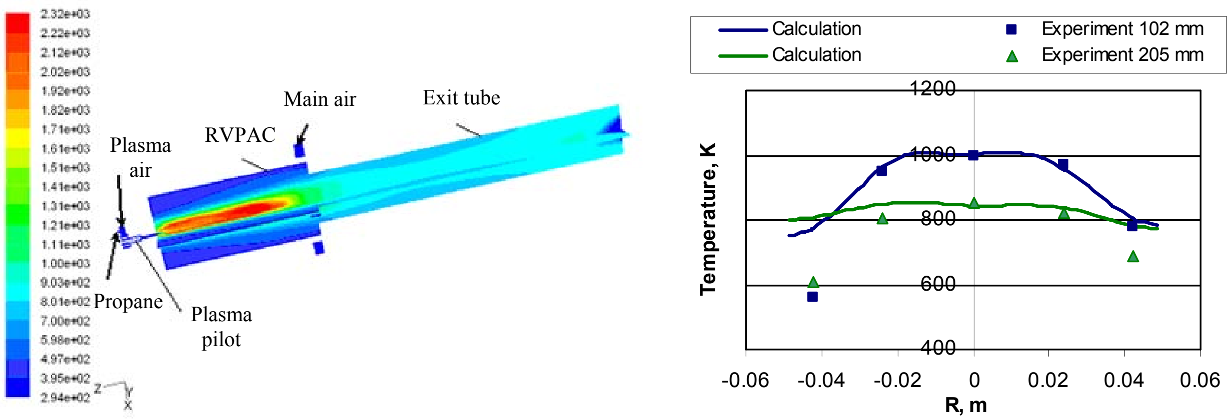


Figure 9. Contours of static temperature (K), and radial distribution of temperature in the exit tube.

CONCLUSION

Experimental tests of the reverse-vortex plasma assisted combustion systems with plasma pilot and spatial arc have been carried out. Selected technology provides "cold walls" operation in a wide range of parameters, and could be scaled up for higher power and pressure operations. Proposed concept of portable RVPAC can provide higher performance, wider turn down ratios, more efficient propellants utilization, decrease combustor and engine weight, demonstrate potential fuel flexibility, satisfy major gravimetric and volumetric density requirements.

Obtained results and recommendations can be used for the RVPAC system operational modes and geometry optimization, perspective combustors design and engineering for propulsion and power generation.

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