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Low-Toxic Combustion Chamber with Rich–Lean Diffusion Combustion

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ABSTRACT
This work investigates into the influence of shape of air supply tubes to microturbine direct-flow tubular combustion chamber on its properties. The studies are based on mathematical simulation of flow and combustion in combustion chamber. The influence of lateral air supply to direct-flow tubular combustion chamber is analyzed. It is revealed that lateral air supply to tubular combustion chamber results in significant increase in hydraulic losses, toxic emissions, temperature heterogeneity at outlet, and certain problems occur related to temperature of some sites of combustion liner. Approaches to improvement of performances of combustion chamber with lateral air supply are discussed. In particular, width extension of annular channel of air supply to inlet of combustion chamber has been considered. The variant with 2.5-fold width of annular channel of air supply allowed to reduce flow strength and to equalize to some extent the velocity profile in the channel, which provided reduction in hydraulic resistance and the temperature of combustion liner wall decreased to permissible level of 1,350 K.

Key words: microturbine, combustion chamber, toxic components, temperature unevenness, mathematical modeling.

1. INTRODUCTION

1.1 Formulation of the problem

Development of microturbines is a challenging trend of ICE development [1]. Improvement of ICE efficiency is based on development of mathematical models aimed at determination of the required properties [2] and adjustment of elements of gas turbine engines [3].

In the scope of the project [4] of 50 kW microturbine, NAMI developed low-toxic, tubular, direct-flow methane-operated combustion chamber. Diffusion, rich-burn, quick-mix, lean-burn (RQL) process takes place in the chamber (Fig. 1) [5-7].

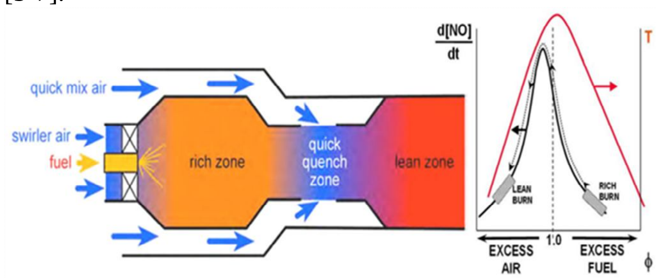


Figure 1: Low-toxic, tubular, direct-flow combustion chamber with rich- lean combustion

While designing combustion chamber, it has been assumed that air at inlet to combustion chamber is characterized by axial direction and the profiles of its velocity and pressure are uniform (Fig. 2a). In the developed microturbine embodiment, air is supplied to combustion chamber sideways: normally to the symmetry axis of combustion chamber (Fig. 2b). Such air supply leads to significant flowrate heterogeneity at combustion chamber inlet with regard to design variant and, as a consequence, variation of its performances.

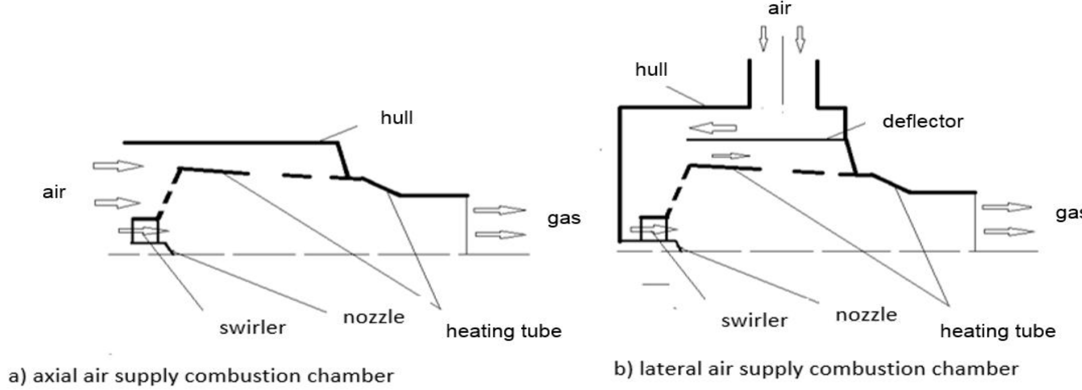


Figure 2: Low-toxic tube combustion chamber with axial and lateral air supply

2. OBJECTIVES

This work is devoted to analysis of the influence of configuration of air supply tubes on the performances of combustion chamber.

3. METHODS

3.1. Mathematical Simulation of Flow and Combustion

The studies are based on predictions. The influence of geometry of air supply was analyzed by mathematical simulation of flow and combustion in combustion chamber.

Stationary, compressible, viscous, turbulent flow of air and gases was simulated in combustion chamber.

Self-ignition delay was not taken into account. Fuel ignition was not simulated. Two-parameter turbulence model based on the Reynolds-averaged Navier–Stokes equations (RANS) [8, 9] and isotropic model of radiation heat exchange were applied. The flamelet model based on ensemble of unidimensional laminar flames [10-12] was used to simulate diffusion turbulent combustion.

The boundary conditions used in the model of combustion chamber are given below:

at chamber inlet:

– total pressure 350,993 Pa;

– total air temperature 977 K;.

at chamber outlet:

– flowrate of air and gas through combustion chamber 0.4152 kg/s;

fuel:

– methane flowrate 0.0025365 kg/s;

combustion chamber walls: adiabatic.

4. RESULTS

The predicted properties of combustion chambers with axial and lateral air supply are summarized in Table 1.

Table 1: Performances of combustion chamber with axial and lateral air supply

	NO emissions [ppm]	Heterogeneity of temperature field at outlet [K]	Hydraulic resistance [%]	Maximum temperature of combustion liner wall [K]
Combustion chamber with axial air supply	7.6	27	1.2	950
Combustion chamber with lateral air supply	13	61	2.6	1,600

The temperature heterogeneity given in the Table was estimated by mass weighted standard deviation from average mass temperature:

$$\Delta T = \langle (T - T_{ave.mass})^2 \rangle^{0.5} \quad (1)$$

where T; $T_{ave.mass}$ were the local and average mass temperatures, respectively.

Emissions of nitrogen and carbon were estimated according to ISO 11042-1 being standard for emission of gas turbine unit [14]. The predicted mass fraction was converted into NO emissions at 15% of oxygen in exhaust:

$$E_{vj15,dry} = \varphi_{i,dry}(20{,}95 - 15)/(20{,}95 - \varphi^{O_2}_{dry}) \quad (2)$$

where $\varphi_{i,dry}$ was the concentration of a considered component i in exhaust gas, $\varphi^{O_2}_{dry}$ was the actual concentration of free oxygen in exhaust gas.

As follows from Table 1, all performances of combustion chamber upon lateral air supply are significantly inferior. Hydraulic resistance increased by 2.2 times, temperature heterogeneity at inlet increased by 2.3 times. Nitrogen oxide emission increased by 1.7 times. In addition, upon lateral air supply, the maximum temperature of combustion liner was unacceptable in terms of operability of metal combustion chamber (1,600 K).

The main reason of this deterioration is significant heterogeneity of flow at inlet and, as a consequence, inside the combustion chamber [13-16]. Figure 3 illustrates the vector velocity field and density of bulk flow (mass velocity) in various cross sections of flow channel of combustion chamber. As seen in the figure, due to heterogeneity in the distribution cavity, the flowrates through the holes of primary and secondary air are also heterogeneous. Therefore, the head of some jets is insufficient to displace flame front, which finally modifies mixing and results in heterogeneity and instability of flame front.

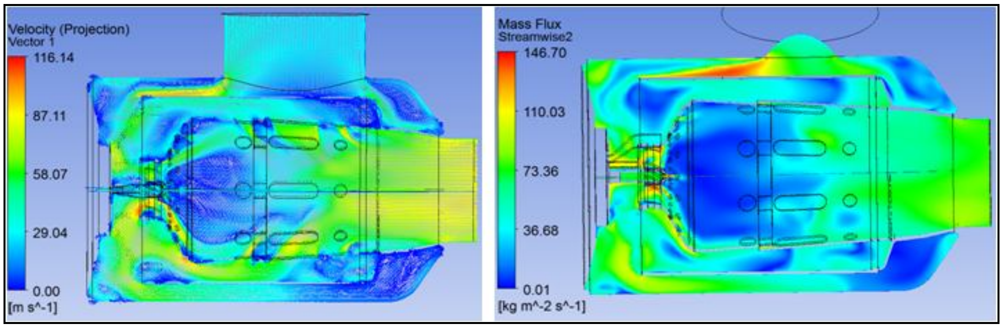


Figure 3: Velocity field (left) and the mass flow density (right) in the combustion chamber with lateral entrance

Figure 4 illustrates the temperature of flame and combustion liner walls. Strong heterogeneity of flame front can be observed caused by heterogeneous distribution of primary and secondary air. In front of slot holes of film cooling, it is possible to observe the areas of increased temperature of combustion liner walls reaching 1,600 K, which exceeds allowable temperature of known heat resistant alloys.

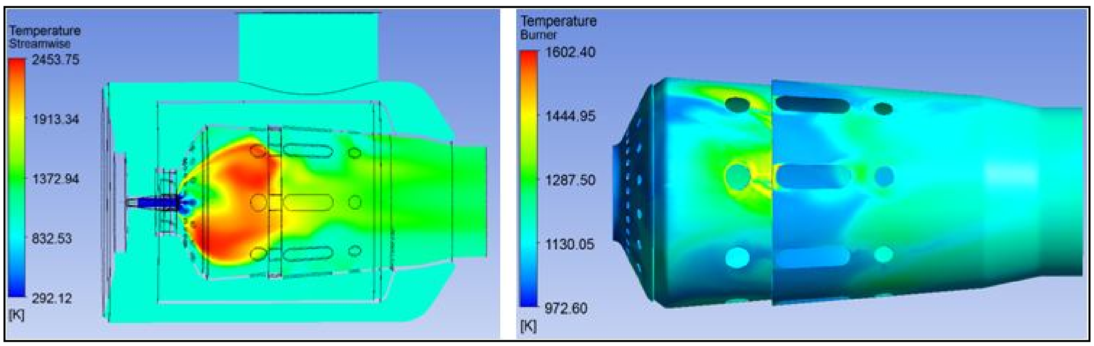


Figure 4: Temperature of the flame (left) and the walls of the flame tube (right) of the chamber.

The velocity fields in Fig. 3, in addition to significant heterogeneity, show existence of areas with high velocities in the annular channel formed by the body and deflector (Fig. 2b). In order to eliminate these areas and, respectively, to reduce pressure losses and heterogeneities of air and gas flows, it was proposed to consider combustion chamber with 2.5-fold width of annular channel.

Figure 5 illustrates velocity distribution in air supply channels for the initial and modified variants of combustion chamber with lateral supply. As seen in the figure, the variant with extended width of annular channel of air supply is characterized by lower velocities and more homogeneous velocity field.

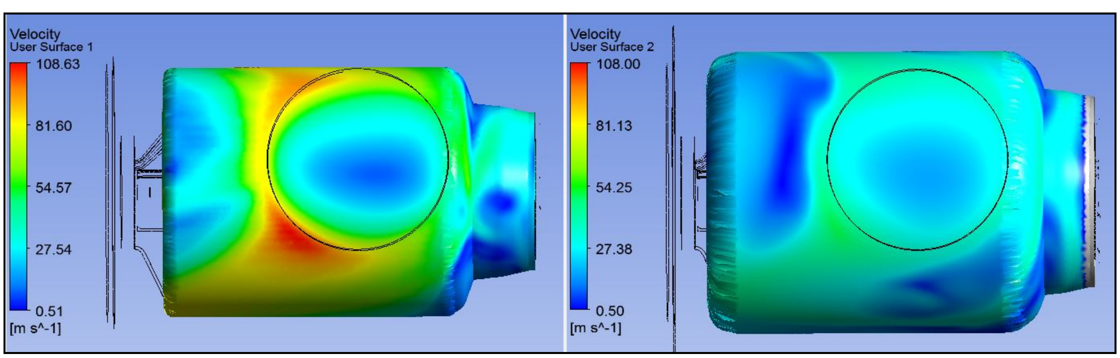
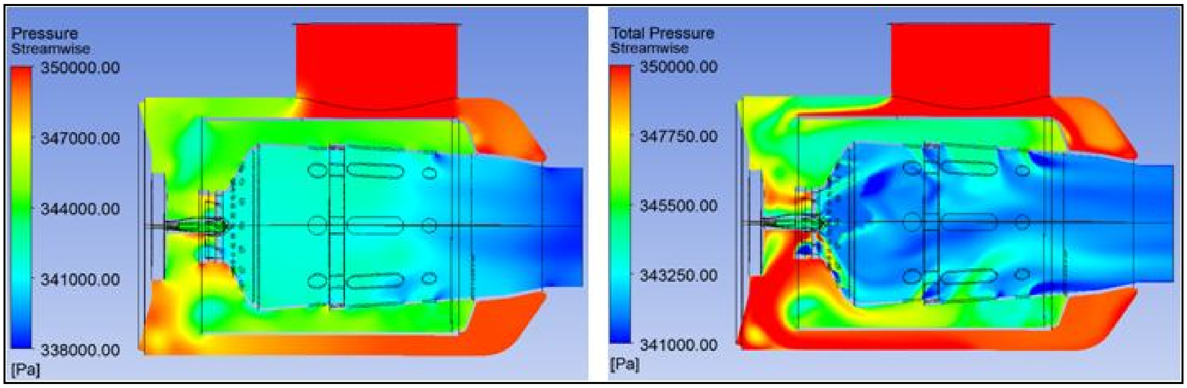
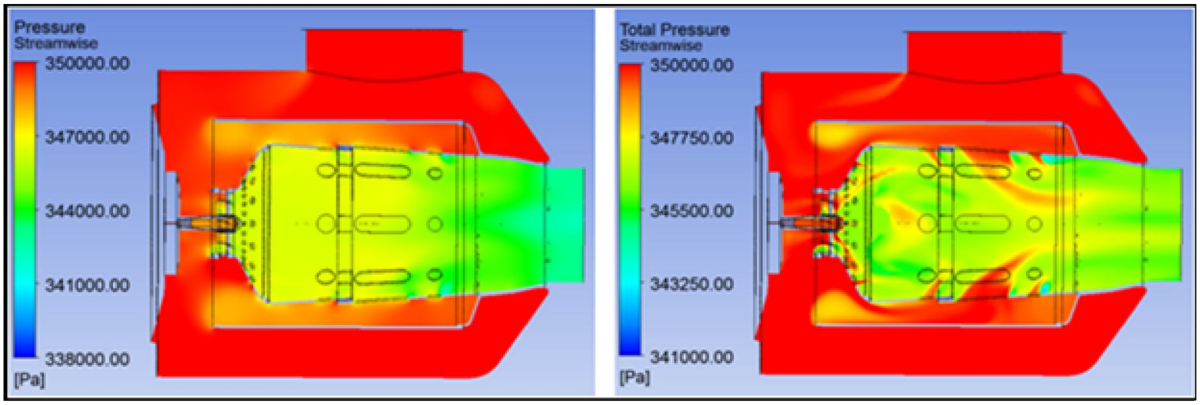


Figure 5: Distribution of speed in the annular gap of the air supply in the initial (left) and in the modified variant (right).

Analysis of pressure profiles in the modified combustion chamber with lateral supply demonstrates that pressure losses in the modified combustion chamber with lateral supply and heterogeneity of pressure fields in air supply channels decreased significantly (Fig. 6, a, b).



a) initial version of the combustion chamber with lateral air inlet



b) combustion chamber with lateral entrance and with increased width of gap (modified variant)

Figure 6: Static (left) and total (right) pressure in revised variant of combustion chamber with lateral air supply.

Figure 7 illustrates the temperature field in the chamber and walls of its combustion liner in the modified variant of combustion chamber with lateral air supply. It can be seen that despite the preserved asymmetry of flame front, the temperature heterogeneity decreased. The maximum temperature of combustion liner walls decreased to 1,350 K, which is acceptable for the alloys used for combustion liners (Fig. 7).

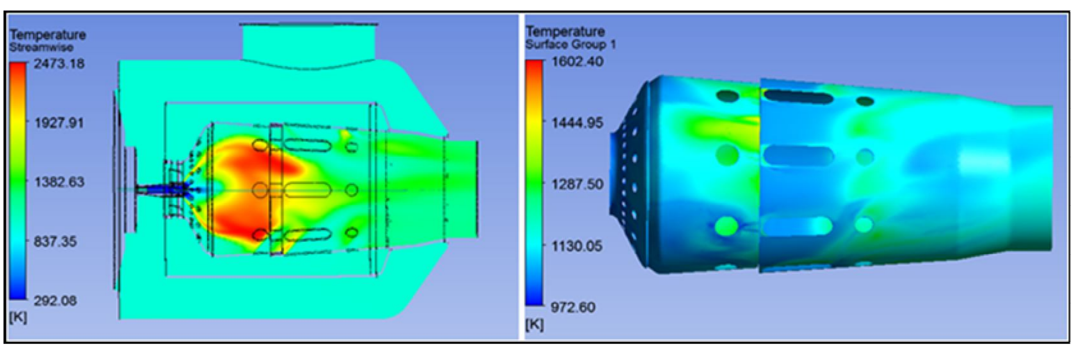


Figure 7: Air (gas) temperature (gas) in combustion chamber (left) and heating tube walls (right) of compressor in the modified variant.

Hydraulic losses decreased in fact to the level of combustion chamber with axial supply (1.3%), mean square heterogeneity at outlet from combustion chamber decreased from 61 K to 47 K. The width extension of annular channel of air supply did not exert any effect on nitrogen oxide emissions, they remained at the level of 13 ppm

5. CONCLUSION

Low-toxic, tubular, direct-flow combustion chamber with diffusion combustion of rich–lean air–fuel mix was analyzed. Three variants of combustion chamber were considered. The first variant was based on axial air supply providing homogeneous fields of velocity and pressure at inlet to combustion chamber. The second and the third variants were based on lateral air. The necessity in such air supply to combustion chamber was stipulated by microturbine arrangement. The third variant differed from the second variant by 2.5-fold width of annular channel of lateral air supply to the inlet of direct-flow combustion chamber.

The predictions demonstrated that performances of combustion chamber deteriorated significantly upon conversion from axial to lateral air supply. There occurred 2.2-fold increase in hydraulic resistance of combustion chamber and 1.7-fold increase in nitrogen oxide emissions. The temperature heterogeneity at outlet from combustion chamber increased by 2.3 times, the temperature of combustion liner walls became unacceptable (up to 1,600 K). As a consequence of modification of combustion chamber by width extension of annular channel, the heterogeneity of gas temperature at outlet was significantly reduced from 61 K to 47 K, the hydraulic losses decreased in fact to the level of combustion chamber with axial supply (1.3%). The width extension of annular channel of air supply did not exert any effect on nitrogen oxide emissions, they remained at the level of 13 ppm.

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