Numerical simulation of synthesis gas/air and methane/air flames for model combustion chamber with swirling flow

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Abstract. This paper reports on the investigation of combustion features of synthesis gas/air and methane/air flames in a model gas turbine combustor with swirling flow via numerical simulation. This combustor developed for experimental investigation of flow, heat transfer and combustion. For synthesis gas combustion ratio of hydrogen and carbon monoxide was 1:1. The equivalence ratio Φ in both cases was 1.5. The combustor contains systems for water- and air-cooling that provides reasonable temperature value of combustor walls in operating mode. The methane/air flame has the lifted V-shape and synthesis gas/air flame has the columnar tubular flame. In practical, the V-shape flames are more often used. To provide more practical combustion regimes for synthesis gas/air mixture it is necessary to increase the fuel-oxidant mixing efficiency in the premixer of the combustor.

1. Introduction

Currently, the development of combined cycle power plants using coal fuel with intra-cycle gasification is a promising area in the energy sector. A synthesis gas obtained after conversion of a hydrocarbon solid fuel (fossil fuel, biomass, municipal solid waste) is purified and combusted in the gas turbine combustor. Operation of advanced power system turbines promises to provide fuel flexibility and to ensure reduced pollutant emission [1,2].

Due to the low calorific value of synthesis gas, attainment of the low emission of pollution and the high-energy efficiency of the combustion chamber of a gas turbine operating on synthesis gas is a complex scientific and technical problem [3]. To solve this problem, it is necessary to develop a model gas turbine combustor that allows providing an experimental investigation of flow, heat transfer and combustion. Moreover, dynamic processes, such as flame flashback and blowout, swirling flow, and combustion instabilities, accompany combustion in the combustion chamber. An important stage of development of model gas turbine combustor is the numerical simulation confirming its operability and reliability.

This work aimed to numerically simulation the flow structure and combustion features of synthesis gas/air and methane/air flames in a model combustion chamber at atmospheric pressure via modern CFD-approach.
2. Methods
The numerical study of the combustion of synthesis gas/air and methane/air flames in a model gas turbine combustor with swirling flow was carried out. Figure 1 shows the 3D sketch of the combustor. The air was supplied in the annular chamber via four holes, whence it gets into the premixer. The fuel was supplied via the central channel. The air and fuel were mixed in the combustor. The nozzle diameter \( d \) of the premixer was equal to 38 mm and the width of the combustor was 180 mm. The mass flow rate of air was 20 g/s. The mass flowrates of synthesis gas (ratio of hydrogen and carbon monoxide was 1:1) and methane were, respectively, 3.7 g/s and 0.8 g/s. The equivalence ratio \( \Phi \) in both cases was 1.5. To provide efficient cooling of the combustor bottom, the water circulation in closed cavities was used. The sidewalls of the combustor were cooled via air that was supplied in the combustor from flat holes.

![Figure 1. Sketch of the model gas turbine combustor with swirling flow (left) and example of unstructured computational grid in central section (right).](image)

For simulation of turbulent flames, the unsteady RANS method with k-ω SST turbulence model was used. As the model of turbulent combustion, a progress variable approach with the FGM model (flamelet generated manifold) was used. To simulate the kinetics of gas-phase reactions, various mechanisms were used (GRI-Mech 3.0 for methane/air flame and H2/CO kinetic mechanism that contains a detailed mechanism of hydrogen oxidation for synthesis gas/air flame). Radiation heat transfer was performed using the method of discrete ordinates that implemented on non-orthogonal grids and it corresponds to the hydrodynamic grids. The absorption coefficient was calculated using the weighted-sum-of-gray-gases model. The unstructured grid (see Fig. 1) was used. The total number of nodes was approximately 3.3 million. The discretization of the transport equations was performed based on a finite volume method. All terms were approximated with the second-order upwind scheme.
The time step was $1 \cdot 10^{-5}$ seconds. The calculations were performed on a computing cluster consisting of 60 high-performance cores.

3. Results and discussions

The spatial distributions of mean pressure, velocity magnitude and temperature in the combustor for methane/air and synthesis gas/air flames were presented, respectively, in figures 2, 3 and 4. The outlet shape of the combustor is close to the classical solid-body nozzle of Vitashinsky and it provides the uniform distribution of pressure inside the combustor. The pressure has a local minimum only at the exit area. Besides, the maximum velocity magnitude is achieved at the combustor exit. In the case of synthesis gas/air mixture combustion the maximum velocity magnitude at 30 % more than for methane/air flame. The temperature fields show sufficient cooling of the bottom and sidewalls of the combustor.

![Figure 2. Spatial distribution of mean pressure for combustion of methane/air (left) and synthesis gas/air (right) mixture for model combustion chamber with swirling flow.](image)

For quantitative comparison of presented combustion regimes, the profiles of mean velocity components and temperature at different distances above the nozzle exit were presented in figure 5. Joint analysis of fields and profiles shows that in the case of methane/air mixture combustion the flame has a conical shape, so-called V-shape [4], and it is stabilized at a certain distance downstream the nozzle exit. All velocity components have a similar magnitude and one can observe a central recirculation zone at the jet axis. The flame stabilized along with the inner shear layer (around the central recirculation zone). In the case of the synthesis gas/air mixture combustion, the jet has a narrow and elongated shape with expansion downstream. The flame macrostructure is the so-called columnar tubular flame [4]. Near the nozzle exit, the axial velocity is 10 times more than radial and tangential components. However, the flow velocity significantly decreases downstream. The maximum temperature is achieved at the jet axis. Presumably, it is coupled with the fuel rate increase in the case of synthesis-gas/air mixture combustion to provide permanent equivalence ratio $\Phi$. 

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Figure 3. Spatial distribution of mean velocity magnitude for combustion of methane/air (left) and synthesis gas/air (right) mixture in the model gas turbine combustor with swirling flow.

Figure 4. Spatial distribution of mean temperature for combustion of methane/air (left) and synthesis gas/air (right) mixture for model combustion chamber with swirling flow.
Figure 5. Profiles of mean velocity components and temperature at different distances above the nozzle exit for combustion of methane/air (up) and synthesis gas/air (down) mixture for model combustion chamber with swirling flow.

In swirl stabilized combustion systems, the V-shape flames have a particular interest, as these flames are more compact and stable. Therefore, the design of the presented model combustion chamber requires significant modifications to provide more practical combustion regimes for synthesis gas/air mixture. It is probably necessary to increase the fuel-oxidant mixing efficiency in the premixer via addition periphery holes arranged in a central channel exit circle. Moreover, necessary to provide fuel supply directly in the annular chamber of the premixer device.

Conclusions

Features of combustion of synthesis gas/air and methane/air flames in a model gas turbine combustor with swirling flow have been studied numerically using modern CFD-approach. The equivalence ratio $\Phi$ in both cases was 1.5. The combustor contains systems for water- and air-cooling. The numerical investigation shows that in both cases (synthesis gas/air and methane/air flames) the temperatures of combustor walls are at a reasonable value. The outlet shape of the combustor provides the uniform distribution of pressure inside the combustor. In the case of methane/air mixture combustion, one can observe the lifted V-shape flame. However, for synthesis gas/air mixture combustion, the flame macrostructure is the columnar tubular flame. The latter regime not so often used in practice compared to V-shape flames. To provide more practical combustion regimes for synthesis gas/air mixture, it is necessary to increase the fuel-oxidant mixing efficiency in the premixer of the combustor.

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