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SIMULATION OF THE PROCESSES OF COMBINED FUEL COMBUSTION AND ANALYSIS OF HARMFUL SUBSTANCES EMISSION*

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Abstract

Prevention of further atmospheric air pollution and reduction of toxic substances emission is one of the goals of state policy in the field of energy. In this regard, the search for new solutions that prevent negative impact on the environment is one of the priority tasks for modern society. An alternative, but less efficient fuel compared to natural gas is biogas extracted from organic waste. The high content of carbon dioxide in biogas reduces the calorific value, while flame detachment from the burner is also observed. One of the promising options for reducing the negative impact of energy on the environment is the combined burning of natural gas and biogas. For the combined burning of natural gas and biogas in operating power-generating boiler, it is necessary to reconstruct the burner devices installed on them. For a high-quality reconstruction of burner devices, it is important to have theoretical data on the effect of combustion combinations on the content of toxic combustion products in the flue gases of power-generating boilers. In this paper, a turbulence model k – ε (realizable) is presented, which allows simulating the combustion process of a fuel-air mixture. The quantitative content of NO_x, CO_2 in the products of combustion of fuel combinations - natural gas, biogas, natural gas / biogas is presented.

Keywords: combined combustion, emissions, turbulence model

1. Introduction

According to (Decree 176, 2017), one of the goals of the state policy of the Russian Federation in terms of reducing the level of threats to environmental safety is: "preventing further pollution and reducing the level of air pollution in cities and other settlements". One of the main objects that negatively affect the environment in cities with 70 % of the country's

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population is energy, the level of development of which determines the country's economic potential, its competitiveness and well-being of the population.

In accordance with the forecast electricity demand for the unified energy system of Russia until 2024, an annual increase in electricity consumption is expected, more than 1.2 % per year. According to the assessment of the needs of thermal power plants (TPP) of the unified energy system of Russia, it is gas that occupies a sustainable position in fossil fuels (more than 72 % to 23-24 % of coal from the total needs of TPPs for fuel), while by 2024 the share of electricity generation at TPPs will increase to 64.8 % (Order 121, 2018). The main source of TPP emissions are flue gases from power-generating boiler, which, depending on the type of fuel burned: nitrogen oxides, sulfur oxides, carbon oxides, benzopyrene, etc.

A promising direction to reduce harmful emissions into the atmosphere is the processing of organic waste and biogas, which in turn can be burned in energy boilers. When biogas is burned without reconstruction of a power plant, difficulties can arise associated with a high content of impurities, which reduces the heat of combustion, as well as a low flame propagation rate, which will lead to flame separation and burner extinction. One of the effective methods of biogas combustion is its combination with natural gas, which in turn will allow to preserve the heat of combustion and the heat balance of the power plant, as well as ensure stable flame burning. In addition, the organization of the joint combustion of natural gas and biogas will reduce the content of toxic combustion products in the flue gases of power plants. A feature of biogas as a fuel is the reduced, in comparison with natural gas, methane content and the presence of carbon dioxide in large quantities.

In (Sigal et al., 2013), the Gas Institute of the National Academy of Sciences of Ukraine in a laboratory conducted a study on the introduction of carbon monoxide into a gas-air mixture, evaluated the prospects of this method of organizing combustion, and concluded that biogas is the most environmentally friendly type of fuel.

Currently, there are no fundamental obstacles to organizing the process of co-burning natural gas and biogas on existing gas-oil boilers of the unified energy system of Russia (except for reconstruction or replacement of burner devices). In this regard, in this paper several options for the combined combustion of fuels in power-generating boiler are considered in order to reduce the negative impact on atmospheric air.

The studies were carried out using the ANSYS Fluent, due to its wide multifunctional capabilities in the modeling of fuel combustion processes, with the ability to evaluate not only the temperatures in the active combustion zone, which are one of the main indicators of the rate of formation of toxic substances, but also the total content of individual chemical elements and their compounds in fuel combustion products. To study thermal and gas-dynamic processes, we use the turbulence model k – ε (realizable), which allows us to simulate the combustion of a fuel-air mixture (Versteeg and Malalasekera, 2007).

2. Computational model

To simulate the combustion process of a swirling fuel-air flow, a mathematical model is proposed consisting (Anderson, 1995; Hoffmann and Chiang, 2000; Chung, 2002) of the continuity equation, Navier-Stokes equation, energy equation.

$$\nabla.\left(\rho\vec{V}\right)=0, \tag{1}$$

$$\nabla.(\rho u\vec{V})=-\frac{\partial p}{\partial x}+\nabla.(\mu\,\mathrm{grad}\,u)+\left(\frac{\partial\tau_{xx}}{\partial x}+\frac{\partial\tau_{xy}}{\partial y}+\frac{\partial\tau_{xz}}{\partial z}\right), \tag{2}$$

$$\nabla.(\rho \mathrm{v}\vec{V})=-\frac{\partial p}{\partial y}+\nabla.(\mu\,\mathrm{grad}\,\mathrm{v})+\left(\frac{\partial\tau_{yx}}{\partial x}+\frac{\partial\tau_{yy}}{\partial y}+\frac{\partial\tau_{zy}}{\partial z}\right), \tag{3}$$

$$\nabla.(\rho w\vec{V}) = -\frac{\partial p}{\partial z} + \nabla.(\mu \text{ grad } w) + \left(\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}\right), \quad (4)$$

$$\nabla.\left[\rho\left(E + \frac{V^2}{2}\vec{V}\right)\right] = \rho\dot{q} + \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) -$$
$$- p\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) + \frac{\partial}{\partial x}[(u\tau_{xx}) + (v\tau_{xy}) + (w\tau_{xz})] + \quad (5)$$
$$+ \frac{\partial}{\partial y}[(u\tau_{yx}) + (v\tau_{yy}) + (w\tau_{yz})] + \frac{\partial}{\partial z}[(u\tau_{zx}) + (v\tau_{zy}) + (w\tau_{zz})]$$

where *u*, *v*, *w* – velocity components by axis *(x, y, z)* consistently, *p* – pressure; *ρ* – density, *μ* – dynamic viscosity, *E* – internal energy, $\dot{q}$ – the rate of volumetric heat addition per unit mass, *T* – temperature, *λ* – thermal conductivity.

Normal stresses:

$$\tau_{xx} = -\rho\overline{u'^2},\ \tau_{yy} = -\rho\overline{v'^2},\ \tau_{zz} = -\rho\overline{w'^2} \quad (6)$$

and shear stresses:

$$\tau_{xy} = \tau_{yx} = -\rho\overline{u'v'},\quad \tau_{xz} = \tau_{zx} = -\rho\overline{u'w'},\quad \tau_{yz} = \tau_{yz} = -\rho\overline{v'w'} \quad (7)$$

where $\vec{V}$ – the velocity vector:

$$\vec{V} = u\text{i} + \text{vj} + w\text{k} \quad (8)$$

Turbulence Model $k-\varepsilon$ (Realizable). The kinetic energy of turbulence k and its dissipation rate ε satisfy the following transfer equations (Versteeg H. K. et al., 2007):

$$\nabla.\left(\rho k\vec{V}\right) = \nabla.\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla.\ k\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k, \quad (9)$$
$$\nabla.\left(\rho\varepsilon\vec{V}\right) = \nabla.\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla.\ \varepsilon\right] + \rho C_1 S_\varepsilon - \rho C_2\frac{\varepsilon^2}{k + \sqrt{v\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b + S_\varepsilon$$

where σ_κ, σ_ε – are the turbulent Prandtl numbers for *k* and *ε*, respectively, $\sigma_\kappa = 1$; $\sigma_\varepsilon = 1.2$; G_k – represents the generation of turbulence kinetic energy due to the mean velocity gradients; G_b – the generation of turbulence kinetic energy due to buoyancy; Y_M – represents the contribution of fluctuation dilation in compressible turbulence to the total scattering rate; S_k, S_ε – user-defined source terms; $C_{1\varepsilon}$, C_2 – constant, $C_{1\varepsilon} = 1.44$, $C_2 = 1.9$; $C_{3\varepsilon}$ – the degree to the buoyancy; μ_t – turbulent (or vortex) viscosity is calculated by combining *k* and *ε* as follows:

$$\mu_t = \rho C_\mu\frac{k^2}{\varepsilon} \quad (10)$$

where C_μ – empirical coefficient, $C_\mu = 0.09$.

3. Research results

Using the design modeler module, a combustion chamber with one combined burner device was simulated, for simultaneous combustion of natural gas and biogas. The combustion chamber is a cylindrical surface with a given constant wall temperature T_{wall} = 617 *K* (the temperature of the coolant in the boiler). The geometric characteristics of the combustion chamber: L = 7.3 *m*; D = 4 *m*. The computational mesh was generated using the Meshing module, a regular conformal mesh was applied using thickening of the mesh elements along the pulling thickness shown in (Fig. 1).

The burner device with a central gas supply contains a channel for supplying natural gas S_{Ch4} = 0.00125 m^2, a channel for supplying biogas S_{biogas} = 0.078 m^2 and a channel for supplying air S_{air} = 0.234 m^2. The burner device is shown in (Fig. 2).

The study simulated both the combined combustion of a mixture of natural gas and biogas, as well as separate combustion of fuels.

Figs. 3-5 presents the results of combustion of fuel combinations with air swirl ω = 300 rad/s, air temperature at the inlet to the burner device T_{air} = 583 *K*. Simulated fuel consumption through the burner for combined combustion of natural gas $Q_{methane}$ = 0.2 kg/s, biogas Q_{biogas} = 0.3 kg/s. The simulated flow rate through the burner when burning only natural gas $Q_{methane}$ = 0.4 kg/s, when burning biogas Q_{biogas} = 0.59 kg/s. The combustion results are presented in a vertical flame section at x = 3 *m* from the burner throat.

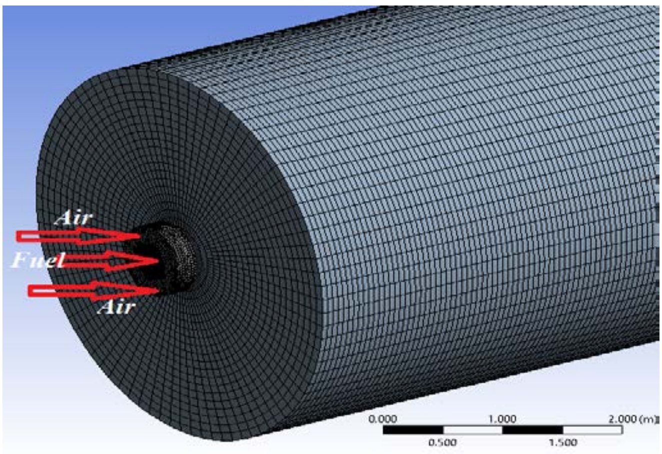


Fig 1. Meshing cylindrical combustion chamber

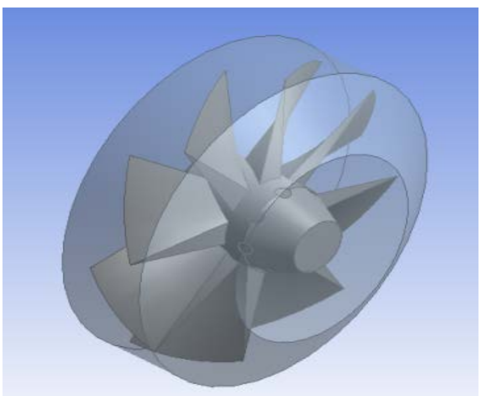
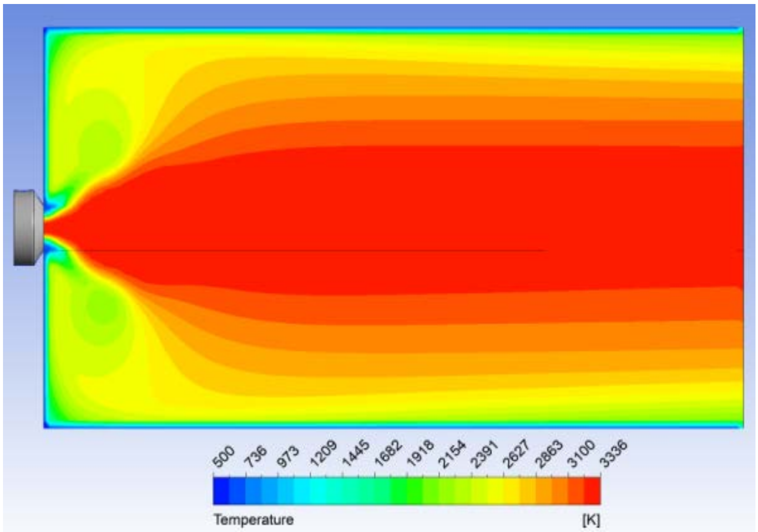
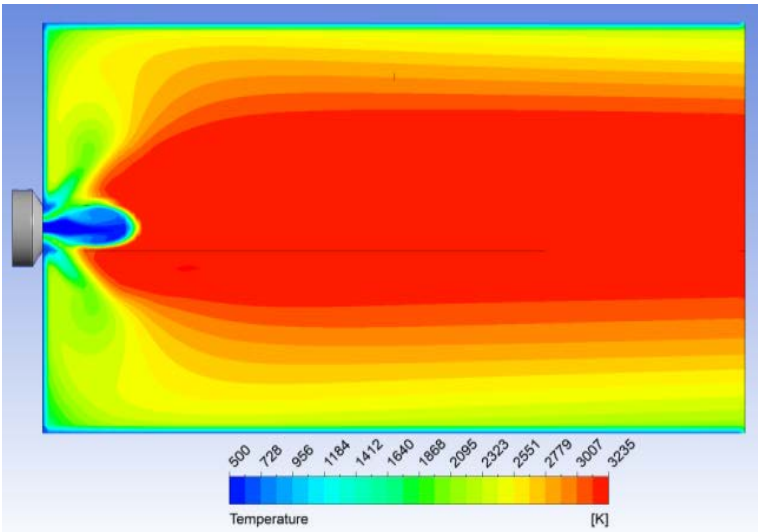


Fig 2. Combined burner device

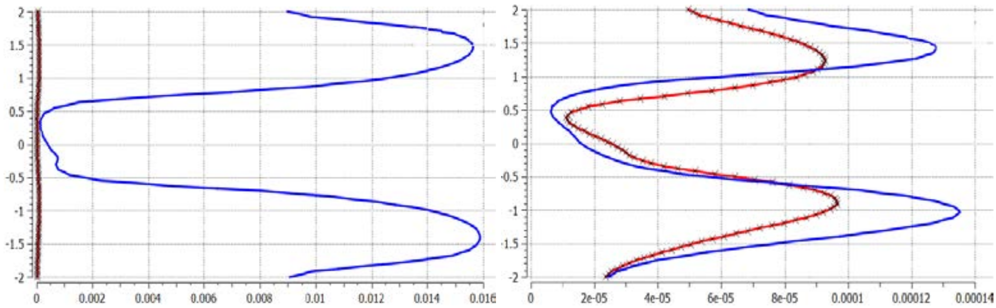


(a)



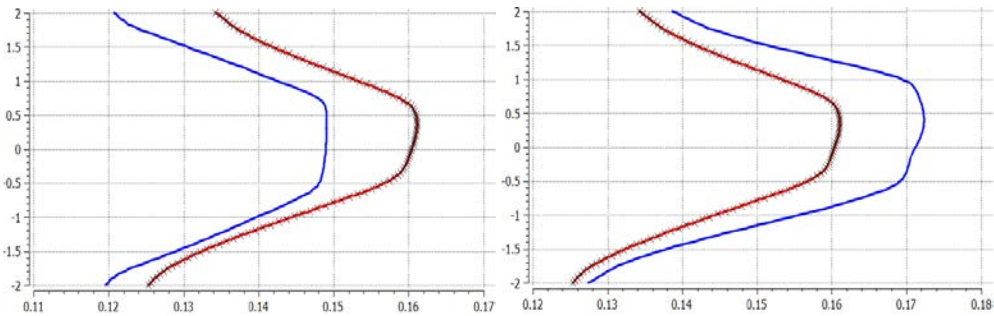
(b)

Fig 3. Temperature distribution in the combustion zone:
a) – combustion of natural gas, b) – co-combustion of natural gas and biogas



(a) (b)

Fig 4. The NO_x content in fuel combustion products: (a) red line – combined combustion of natural gas and biogas; blue line – burning of natural gas; (b) red line – combined combustion of natural gas and biogas; blue line – burning of biogas. Abscissa - Mass Fraction of Pollutant NO_x, ordinate – vertical flame section



(a) (b)

Fig 5. The CO_2 content in fuel combustion products: (a) red line – combined combustion of natural gas and biogas; blue line – burning of natural gas; (b) red line – combined combustion of natural gas and biogas; blue line – burning of biogas. Abscissa - Mass Fraction of Pollutant CO_2, ordinate – vertical flame section

4. Conclusion

Based on the results obtained a significant difference in the values of NO_x content in the combustion products can be noted, which is justified primarily by a decrease in the temperature in the center of the flame, which is the main indicators of the rate of formation of NO_x formation in the power-generating boiler. The decrease in temperature in the active combustion zone is explained by the presence of CO_2 in biogas, which is a distinctive feature of this type of fuel.

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