Mathematical Modeling and Research of Improving the Efficiency of Fuel Combustion in Modern Burners

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Abstract- In the modern world, the requirements for NOx emissions for thermal power plants and power equipment are becoming more and more stringent. Various measures are being developed to improve the efficiency of fuel combustion in boiler plants. Due to the high cost of conducting a physical experiment, and in some cases with the impossibility of conducting them, mathematical modeling is carried out. In this paper, a digital twin of the TGMU-464 boiler plant in the StarCCM+ commercial software package is used to simulate the combustion of gaseous fuel. As a result of calculations, technical solutions are proposed to improve the efficiency of fuel combustion at existing power plants in order to reduce background gas emissions.

Keywords – Combustion chambers, Burner devices, Vortex flow, Mathematical modeling, Numerical research

I. Introduction

With the tightening of environmental requirements for fuel and energy companies, the requirements for maintaining the operating modes of power equipment are increasing. Before the coronavirus pandemic, electricity consumption was growing at a rate of 1.9% per year, while pollutant emissions increased at a rate of 1.4% per year [1]. Particular attention is paid to solid fuel thermal power plants, where it is required to clean flue gases from harmful impurities, especially from ash. As a result of fuel combustion in the combustion chamber, the concentration of nitrogen oxides is determined by the oxygen concentration, the temperature level in the core of the flame, and the residence time of the combustion products in the high temperature zone. The following reactions of formation of lower nitric oxide occur in the combustion chamber:

$$N_2O+O = NO+N \qquad (1)$$

$$N+O_2 = NO+O \qquad (2)$$

Reaction (1) involves atomic oxygen, which is formed at high temperature as a result of the dissociation of oxygen molecules in the air entering the furnace. The NO formed as a result of the reaction in the combustion core (2) will not be able to be further oxidized within the gas path of the boiler. Additional oxidation to the more toxic NO2 occurs in the atmosphere. To increase the efficiency of energy production in the world, such trends as hydrogen energy are actively developing (the heat of combustion of hydrogen is three to four times higher than that of coal and natural gas), coal gasification (the chemical conversion of coal into combustible gas increases the fuel efficiency from 36 to 50 %), biofuels (fuel mixtures based on landfill gases and products of thermal decomposition of industrial and municipal waste). But a reduction in the emission of nitrogen oxides can be achieved by the rational organization of combustion processes in boiler plants through the following measures: 1) lowering the temperature of heating the air entering the furnace to acceptable values; 2) reduction of the excess air coefficient in the combustion device to the minimum possible in terms of ensuring the completeness of fuel combustion; 3) the use of two-stage combustion; 4) flue gas recirculation. There are also methods for reducing NOX to N2 using urea or ammonia. Flue gas recirculation has been widely used, despite the increase in the cost of driving an additional smoke exhauster.

Considering the increasing cost of emissions of pollutants into the atmosphere, the ESG agenda is actively developing in the world. By the early 2000s, there were only 20 ESG-rated companies in the US, and by 2020 this number has grown to almost 800. The average ESG rating has doubled over 20 years, which is attributed to the growth in the volume, quality and availability of data. According to Corporate Knights, in 2021, the top five were: French engineering company Schneider Electric, Danish multinational energy company Ørsted A/S, Brazilian national bank Banco do Brasil SA, Finnish oil and gas company Neste Oyj, international design professional services company, architecture and consulting Stantec Inc [4].

In view of the high cost of carrying out full-scale experiments for testing the combustion regimes in boiler furnaces, where the process of convective mixing, which depends on the design of the burners, is decisive, numerical research and the use of machine learning are of particular importance. Mathematical modeling of the processes of combustion of various fuels in combustion devices allows you to search for the most efficient parameters of the power plant, to assess the level of emission of harmful substances. Machine learning makes it possible to manage large amounts of data obtained as a result of natural and numerical experiments on various spatiotemporal scales in order to reveal hidden patterns for studying combustion processes [5].This makes it possible to carry out multiscale integrated multiphysics modeling, that is, in fact, to create a digital twin of a power plant [6].

As an object of study, a power boiler of the TGME-464 type with a new modification of the GMU-45 burner were chosen. These boilers are widely represented at Russian thermal power plants. Natural gas is considered as fuel.

The rest of the paper is organized as follows. Choice of mesh and combustion model are explained in section II. Results are presented in section III. Concluding remarks are given in section IV.

II. CHOICE OF MESH AND COMBUSTION MODEL

In order to obtain adequate results, the regime map of the operating energy boiler TGME-464 was used as the initial data. The computational experiment used the Flamelet Generated Manifold (FGM) model, which is predominantly used for premixed flames. The computational mesh was generated using the "Mesh" module, a conformal mesh was applied with the use of zonal thickening of mesh elements. The computational area is divided into three zones: the first is the densest mesh for the burner, since the fuel-air mixture flows are mixed and swirled in it; the second is the zone along the axis of the burner in the center of the combustion chamber at the exit from it, since this zone has the highest speeds and temperatures; the third is the zone with the least dense mesh in the rest of the combustion chamber. As the base size for the mesh, a mesh step of 0.5 m was chosen; with an increase in the base size, the accuracy of calculations decreases, and with an increase, the time spent on calculations increases. The number of elements in the simulated combustion chamber with one burner device was 23,626,694 cells.For the calculation with the base size, 96 hours were spent on a high-performance computer based on AMD7713 processors.

III. RESULTS

On figures 1, 2 shown the TGME-464 boiler with a new modification of the GMU-45 burner.

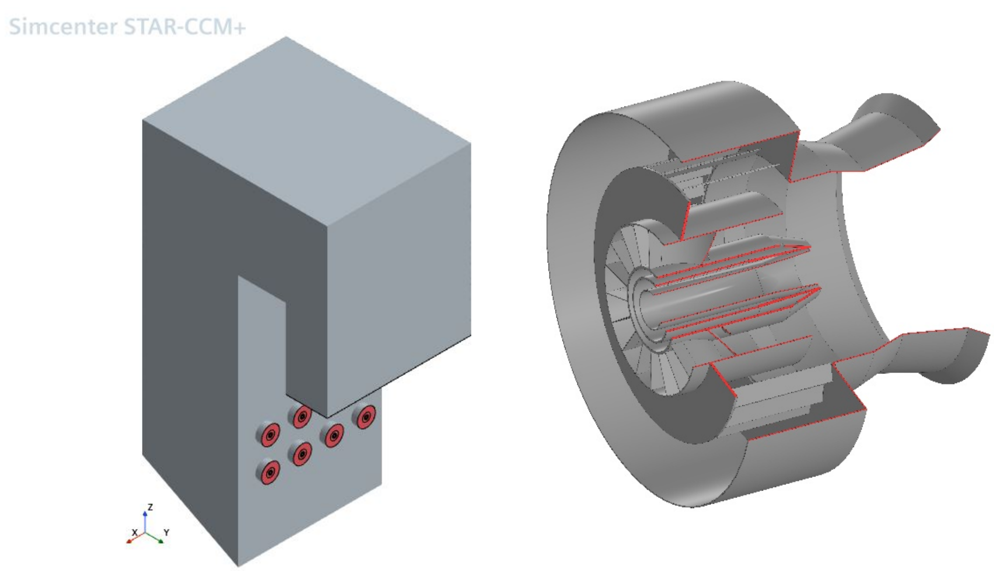

Figure 1. 3d models: (a) - TGME-464 boiler unit; (b) - a new modification of the burner GMU-45

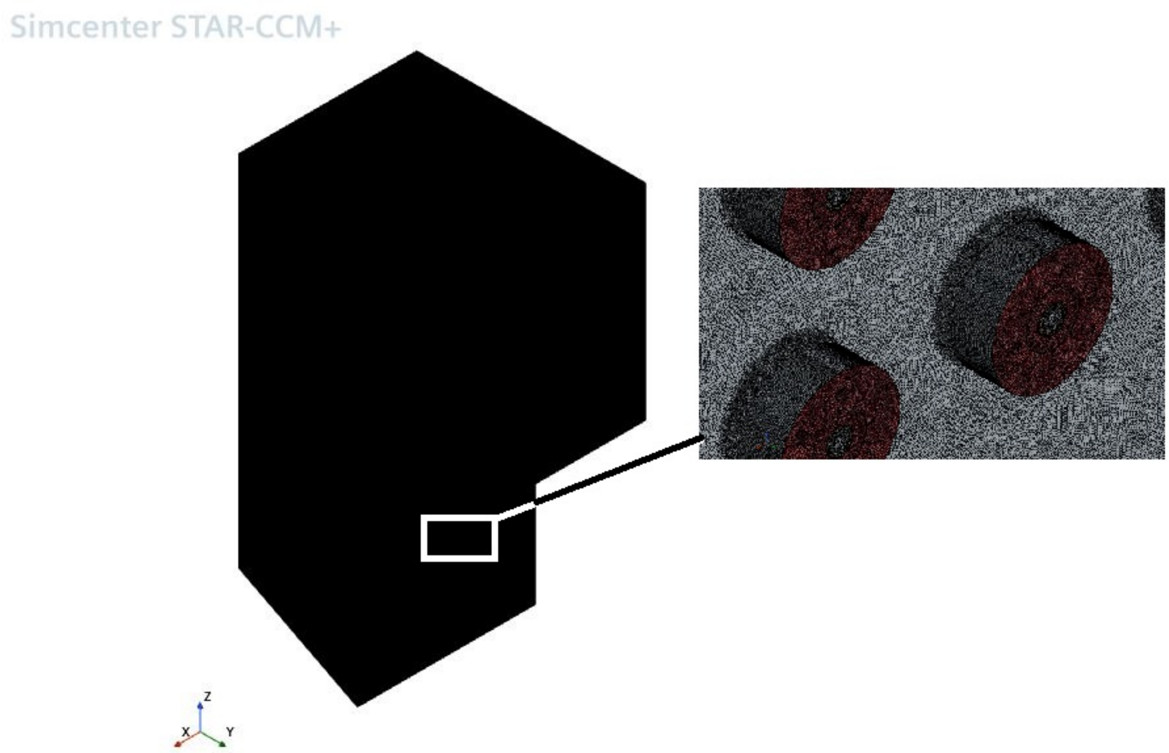

Figure 2. Mesh model of the TGME-464 boiler unit with 23,626,694 cells

Figure 3 show the results of computational experiments with excess air coefficient α = 1.03, gas flow rate through one burner device 4550 m3/h (corresponds to the steam load of the TGME-464 power boiler equal to 470 T/h), air temperature at the burner inlet T = 492÷500 K.

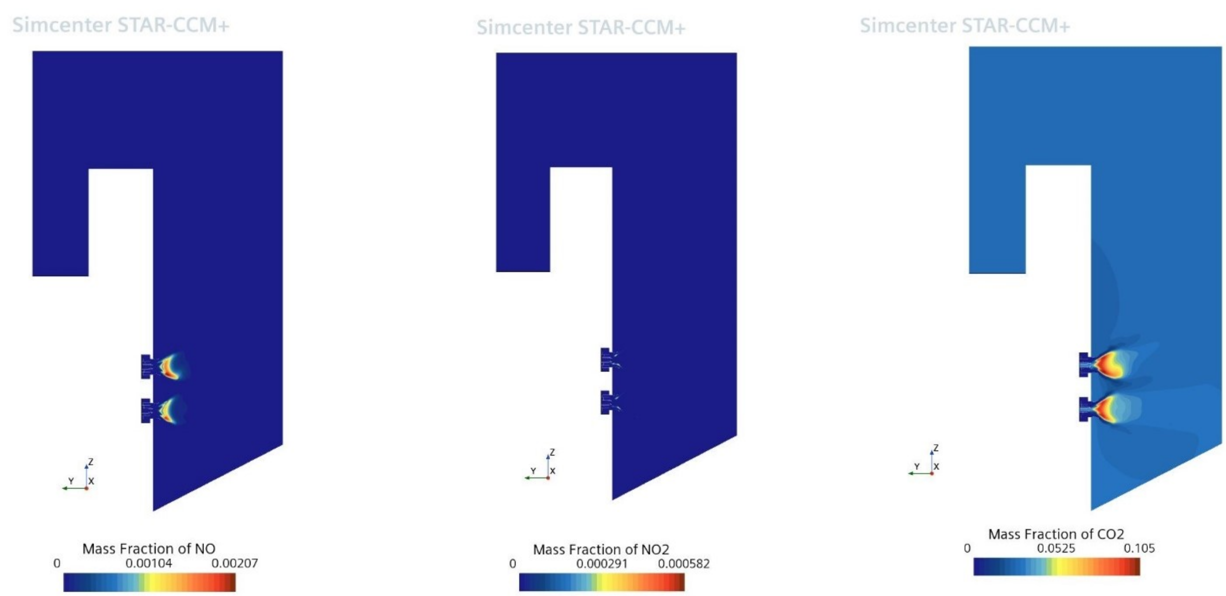

Figure 3. Distribution of various greenhouse gases in the combustion chamber of the TGME-464 boiler unit along the flame axis

As we can see from figure 3, this modification of the burner device allows us to burn natural gas more efficiently, reducing the formation of greenhouse gases.

A further increase in the efficiency of NOx suppression is not possible by increasing the degree of supply of recirculation gases, due to the achievement of the maximum performance of the blower fan at a given heat load. An increase in the efficiency of NOx emission suppression can be achieved by lowering the local temperature during the implementation of organizational and technical measures, such as reorganization of the recirculation degree, reconstruction of burners, and changes in the design of the burner slit.

IV.CONCLUSION

In this work, a solid model of the TGME-464 boiler unit with a new modification of the GMU-45 burner was developed. An analysis of the content of pollutants during operation on natural gas in the Star-CCM + environment was carried out. This modification of the burner allows more efficient fuel combustion, reducing the formation of greenhouse gases.

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