Modeling of Combustion Processes of Gas and Alternative Fuel in Power Plants

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Abstract- The fuel combustion process is a combination of chemical kinetics, heat and mass transfer, fluid dynamics and turbulence processes. The search for alternative solutions in this case is dictated by the complexity of the problem. A furnace device is a complex gas-steam-water heat exchange device. There are various methods for mathematical modeling of furnace and hydro-gas-dynamic processes, most of them model the turbulent flow of a mixture of gases and chemical kinetics. Due to the complexity of the combustion theory associated with the high laboriousness of obtaining analytical solutions in the development of new furnace devices, the experimental approach with the calculation of heat and air balances and the main overall dimensions of the furnace devices previously prevailed. At the same time, modeling of combustion processes is complicated by the simultaneous occurrence of the processes of mixing fuel with air, combustion, and heat and mass transfer. In this regard, the development of an adequate mathematical model and a problem-oriented set of programs will make it possible to obtain a solution to this problem. The paper presents the results of modeling the combustion of gaseous fuels in power and hot water boilers in the StarCCM+ and OpenFoam environments. Burner devices of the GMU-45 and GDS-100 types were used for the study.

Keywords – Mathematical model, Combustion, Burner, Methane-hydrogen mixture, Emission of pollutants

I. INTRODUCTION

The fuel combustion process is a combination of chemical kinetics, heat and mass transfer, fluid dynamics, and turbulence processes [1]. As a result, the general mathematical model includes the equations of physics of these processes, which are solved conjugately. The search for alternative solutions in this case is dictated by the complexity of the problem.

Mathematical modeling is a reliable tool for studying the combustion process. There are several methods for mathematical modeling of furnace and hydro-gas-dynamic processes, which are described in [1–11]. Most of them model the turbulent flow of a mixture of gases and chemical kinetics.

Combustion is considered as the propagation of a flame front from hot combustion products to a cold mixture of fuel and air, which is characterized by the propagation velocity of a turbulent flame front [2]. In [3], a model is proposed in which the average rate of formation of combustion products is proportional to the rate of decay of a turbulent vortex. The EDC combustion model assumes that the reaction occurs in turbulent structures, conventionally called "small-scale". Using the combustion models EDM and EDC, adequate results were obtained when calculating the characteristics of a turbulent flame [7].

Diffusion combustion means that the reactants are fed into the combustion chamber separately. The rate of reactions depends on the degree of mixing of fuel with air [4, 5]. In this model, the convection and diffusion timescales are roughly the same, while the chemical timescales are much smaller.

An alternative approach to modeling the combustion process is to use transport equations describing convection, diffusion, and source terms for each mixture component. In this case, reactions involving mixture components can be described by direct modeling using the Arrhenius equation [1].

To describe the hydrogasdynamics of the combustion process, two approaches are currently used: Euler, which uses the equations of balance of mass, momentum, energy, and concentrations of gas components, and Lagrange, which allows one to describe the motion and heat and mass transfer of individual particles. To describe turbulence, a two-parameter k-ε turbulence model is mainly used, and for modeling radiative heat transfer, a transfer model is used [6]. Thus, the mathematical formulation of the problem is reduced to a system of nonlinear differential equations written taking into account chemical reactions, including the equation of continuity and motion of a viscous medium, the equations of heat and mass transfer and diffusion for the components of the reacting mixture and reaction products, taking into account thermal radiation and the multiphase nature of the medium, the k-ε equations - models of turbulence, as well as equations of state and equations of chemical kinetics that determine the intensity of nonlinear sources of energy and matter.

Much attention is paid to the combustion of hydrogen. As an important source of renewable energy, hydrogen is advancing along with the global clean and low carbon energy trend. Excess energy from wind and solar power plants can be stored as hydrogen to be injected into natural gas. Considering the development of hydrogen energy, it is predicted that CO_2 emissions will be reduced by 20% by 2050 [13]. Hydrogen is considered an attractive fuel due to its wide range of flammability and environmental friendliness, since only water vapor is produced when burned. In [14], the efficiency of an oxyhydrogen gas burner is studied. With a high hydrogen content in the fuel, the burning rate and temperature must be controlled by the burner design. Hydrogen can be used as a partial replacement for natural gas or LPG. In the balance of electricity generation, gas turbine plants will continue to retain a significant share. Salvatore Carusotto, Prashant Goel et al. [15] et al. investigated the combustion characteristics in a gas turbine burner without pre-mixing, which is designed for natural gas when fed with a mixture of NG-H2, while the hydrogen content was taken from 0 to 50% by volume. Based on engine performance data, a CFD model of a steady-state combustion process was proposed with a reduction in fuel mass consumption by up to 17%. When fuel is mixed with hydrogen at a given temperature at the turbine inlet, an increase in the peak temperature to 800 K is noted, as well as an increase in the velocities of the combustion products. At the same time, as hydrogen was added, the flame became more intense.

The rest of the paper is organized as follows. Mathematical model is explained in section II. Experimental results are presented in section III. Concluding remarks are given in section IV.

II.MATHEMATICAL MODEL

The problem is modeled in a three-dimensional, stationary, adiabatic formulation. The processes of heat transfer, chemical kinetics, hydrogasdynamics, considering turbulence, are considered together.

The statement of the mathematical problem of the physical combustion process is formulated asequations of fluid dynamics [9]. The standard k-ε model is chosen to describe turbulence. When choosing the turbulent exchange intensity factor æ, by default, usually taken as 0.4 for standard conditions, options are possible if the conditions differ from the standard ones and have features. So, the combustion of alternative fuels, biogas, biohydrogen can be accompanied by flame instability and pulsations. To consider turbulent flame pulsations, such a characteristic of pulsations as the shifted Hurst exponent H* [12] can be used. As a combustion model, it is proposed to use the vortex decay model (3-step eddy break-up model or 3-step Eddy Break-Up) [10]. According to the Eddy Break-Up model, the components are immediately burned when mixed. The reaction rate is modeled using an expression that considers the turbulent process of micromixing. The system of equations with boundary conditions is solved by a conjugate numerical method in the STARCCM+ environment with respect to the components of velocity, temperature, content of CH_4, CO, CO_2, H_2, H_2O, N_2, O_2, as well as turbulent characteristics.

III. EXPERIMENTAL RESULTS

In this work, the combustion of a methane-hydrogen mixture was simulated on a TGME-464 power boiler and a GMU-45 burner, as well as a hot water boiler with a GDS-100 burner.

Figure 1 shows a solid model of a GMU-45 type burner.

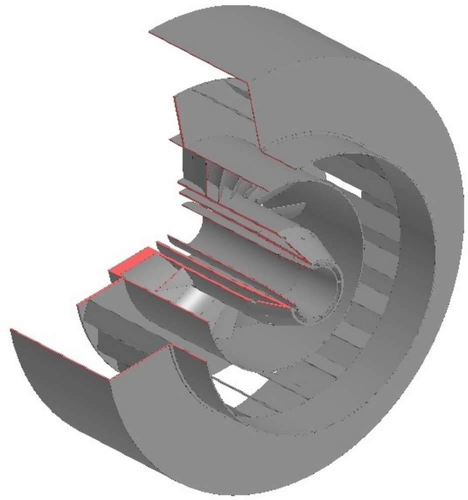

Figure 1. Solid model of the burner device type GMU-45.

Figure 2 shows a solid model of a GDS-100 type burner.

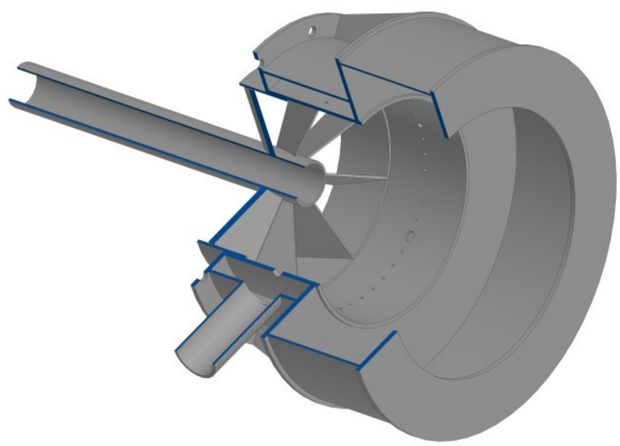

Figure 2. Solid model of the burner device type GDS-100.

Figures 3-5 show the results of modeling the combustion of a methane-hydrogen mixture in the GMU-45 burner with flue gas recirculation r = 10% at different hydrogen content, indicating the distribution of temperature, CO_2 and NOx along the combustion chamber. In the first experiment, only methane was burned at a calculated rate of 0.556 kg/s, in the second experiment, the calculated CH_4 feed rate was 0.5523 kg/s, and the H_2 feed rate was 0.0004 kg/s, in the third experiment, the calculated CH_4 feed rate was 0.5490 kg/s, and the feed rate of H_2 is 0.0008 kg/s.

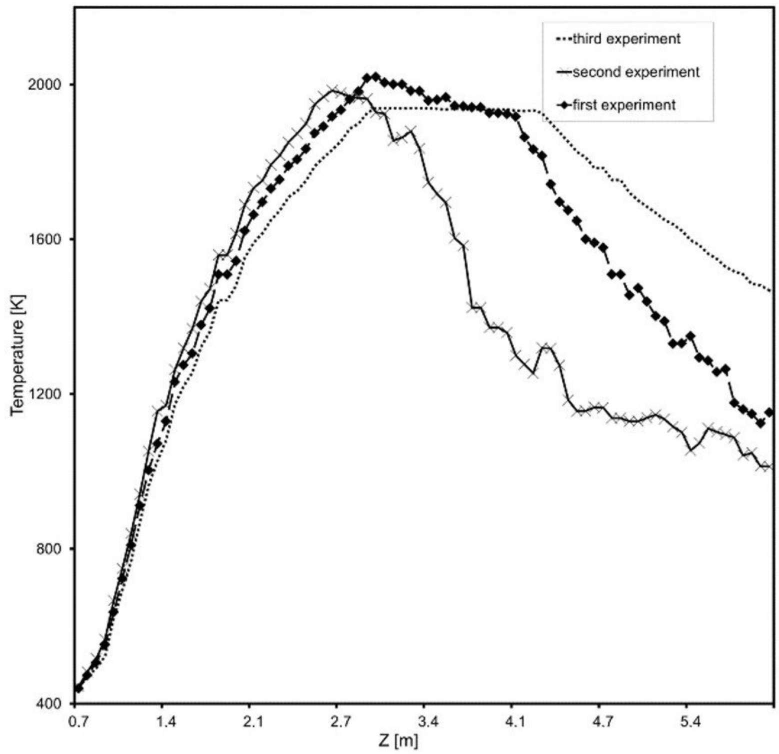

Figure 3. Temperature distribution in the core of the torch during combustion of methane-hydrogen mixture

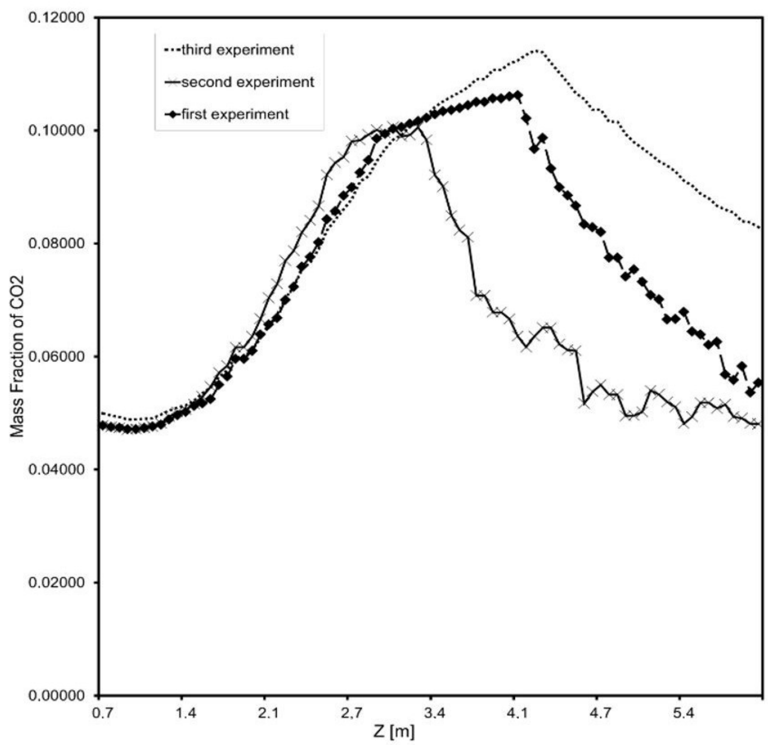

Figure 4. Distribution of CO2 in the flare core during combustion of methane-hydrogen mixture

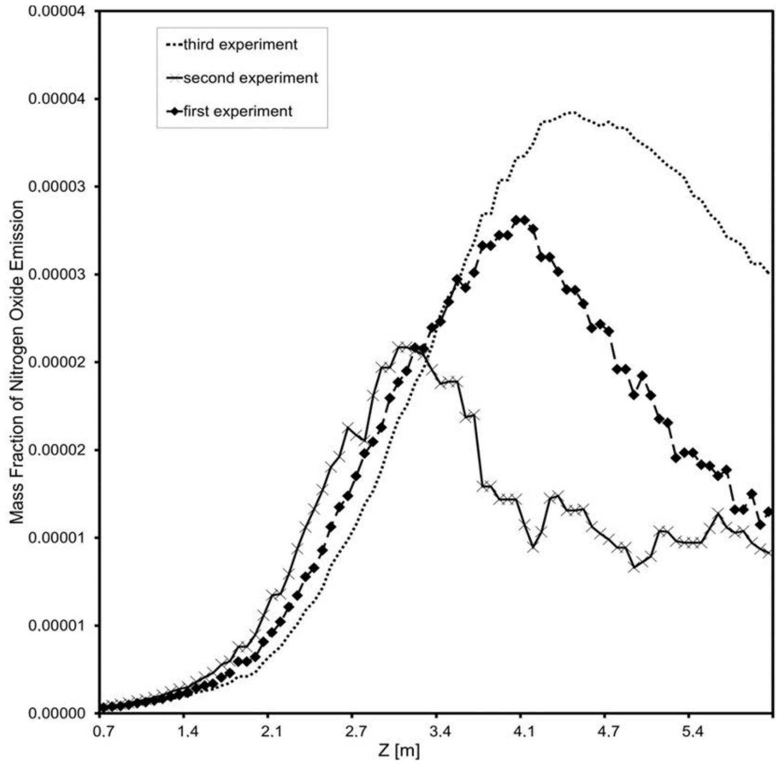

Figure 5. Distribution of NOx in the flare core during combustion of methane-hydrogen mixture

As can be seen from Figures 3-5, with an increase in the proportion of hydrogen in certain modes, a decrease in temperature in the core of the flame, as well as a decrease in pollutant concentrations, can be observed.

IV.CONCLUSION

The proposed alternative approach to modeling the turbulent exchange intensity factor will make it possible to consider the features of the combustion of unconventional fuels, such as methane-hydrogen mixtures.

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