Hindawi
International Journal of Chemical Engineering
Volume 2022, Article ID 9123639, 12 pages
https://doi.org/10.1155/2022/9123639

Research Article

Investigation of the Characteristics of a Gas Turbine Combustion Chamber with Steam Injection Operating on Hydrogen-Containing Mixtures and Hydrogen

Serhiy Serbin ,[1] **Kateryna Burunsuz** ,[1] **and Daifen Chen** [2]

[1] *Department of Turbine Units, Admiral Makarov National University of Shipbuilding, Heroes of Ukraine Ave. 9, Mykolayiv 54025, Ukraine*
[2] *School of Power and Energy, Jiangsu University of Science and Technology, 2 Megnxi Road, Zhenjiang 212003, Jiangsu, China*

Correspondence should be addressed to Serhiy Serbin; serbin1958@gmail.com

Received 15 August 2022; Revised 20 November 2022; Accepted 9 December 2022; Published 17 December 2022

Academic Editor: Badie I. Morsi

The article is devoted to the investigation of the characteristics of a gas turbine combustion chamber with a steam injection when operating on hydrogen-containing mixtures and pure hydrogen. The parameters of a cannular combustion chamber with a separate injection of ecological and energy steam were studied to ensure the stable and ecologically clean chamber's operation without the formation of flashback zones. The injection of ecological steam in the area of the vane swirler of the flame tube for the diffusion-type combustion chamber makes it possible to provide low emissions of nitrogen oxides at significant concentrations of hydrogen in its mixtures with natural gas, even if the maximum gas temperature in the primary zone of a combustion chamber increases. For the investigated chamber's operating modes, the calculated carbon monoxide emission does not exceed 18.1 ppm. Emissions of nitrogen oxide when the hydrogen content changes from 0 to 50% initially decrease from 36.1 to 17.8 ppm due to increased steam injection to the combustion zone and then increase to 38 ppm when operating on pure hydrogen. An increase in the nonuniformity of the temperature field at the combustion chamber outlet with an increase in the hydrogen content in the mixture with natural gas was noted.

1. Introduction

The use of environmentally friendly gas turbine energy modules operating on hydrogen-containing gases and hydrogen is one of the world's promising areas for improving the efficiency of transport and stationary decarbonized energy systems. This is especially relevant today for the creation of promising gas turbine plants for floating production storage and offloading (FPSO) vessels and autonomous mobile energy means for complex and rapid supply of electricity, heat, and cold to various industrial facilities, as well as for transportation of gaseous hydrocarbon resources, including pure hydrogen. The creation of modern decarbonized gas turbine modules involves the development of fundamentally new design schemes of low-emission combustion chambers operating on hydrogen-containing gases and hydrogen.

To improve the efficiency of gas turbine units, various methods are proposed for complicating their thermal schemes. One such method is the use of a complex thermodynamic cycle with steam injection into a combustion chamber. The steam generated in the waste heat boiler is fed into the high-pressure path after the compressor. Such steam-injected gas turbines (STIG) have high efficiency and specific power [1], which allows them to be used competitively in various fields, including FPSO vessels. The steam, together with the combustion products, is usually released into the atmosphere, which leads to the loss of heat from the evaporation of this water and the water itself. In installations of the "Aquarius" type [2, 3] this shortcoming is eliminated by the introduction of a special contact condenser, which condenses the vapor contained in the exhaust gases, and the water returns to the installation cycle. The "Aquarius" gas-steam turbine units are the most promising units for use in places where there are difficulties in preparing large amounts of boiler water, as they allow not only to return the boiler water to the cycle but also to obtain excess distilled water due to condensation of moisture produced by fuel combustion.

The development of decarbonized energy systems leads to the potential possibility of using gas turbine units of the "Aquarius" cycle operating on hydrogen-containing mixtures and pure hydrogen. It is known that low-emission gas turbine combustion chambers operating on the principle of a lean pre-prepared air-fuel mixture have a significant drawback. This disadvantage is associated with the possibility of the formation of a flashback zone in the region of preliminary mixing of fuel with an oxidizer. This disadvantage is especially significant at high hydrogen contents in the mixture and when operating on pure hydrogen.

The destabilizing effect of hydrogen additives on the flame propagation of pre-mixed mixtures was Micro-Mix, as described in [4]. It was noted [5] that the known structural schemes of combustion chambers of gas turbine engines cannot be used for hydrogen combustion without modification. This paper proposes a special Micro-Mix technology to prevent flame flashback. The same conclusion was presented in [6], where it was shown that the basic design of a fuel-burning device cannot be reliably operated on pure hydrogen, since the flame penetrates the premixing channels and causes damages. As a result of the studies carried out in [7, 8], it was concluded that it is expedient to modify the modern Dry Low NOx (DNL) low-emission burning system when converting gas turbine combustion chambers to use hydrogen-containing fuel and pure hydrogen. For this, an interesting DLN micromix method of fuel combustion is proposed, which is based on the use of a large number of miniaturized diffusion-type burners. The authors emphasize that the diffusion type of combustion of hydrogen-containing fuels is preferable since the probability of the formation of flashback zones sharply decreases. Dispersion of the hydrogen injection along the length of a combustion chamber led to an improvement in the temperature level of the walls and significantly reduced the coefficient of nonuniformity of the temperature field at the combustion chamber's outlet.

Note that in recent years, computer simulation principles are often used to predict the characteristics of the working process in combustion chambers operating on hydrogen-containing gases and hydrogen. For example, in [9], computational fluid dynamics (CFD) calculations of the thermal behavior of combustion chamber casings when operating on hydrogen and a comparison of their characteristics when operating on natural gas are carried out. The results of full-scale tests are used to verify the models. In [10], three-dimensional CFD calculations of a fuel-burning device operating on hydrogen and methane are carried out. It is noted that when working on hydrogen, there is an increase in the velocity of the working fluid inside the chemical reaction zone.

Article [11] reviewed the issue of reducing the probability of flashback formation when hydrogen is used as a fuel. Three types of burners are considered, differing in the air flow swirling rate. It was found that with a decrease in the rate of swirling, the probability of flashback decreases. However, in this case, an increase in the instability of the flame front position in a combustion chamber and the occurrence of undesirable parameter fluctuations is possible.

One way to reduce the flashback risk is to inject steam to the chemical reaction zone. Combustion of various mixtures of natural gas with hydrogen in dry and steam-diluted operating modes for rich-quench-lean (RQL) and pre-mixed combustion chambers is studied in [12]. Steam dilution is very effective in reducing nitrogen oxides for both natural gas and pure hydrogen. Steam reduces the reactivity of hydrogen and even relatively low steam content can prevent flashback.

Thus, one of the significant problems that arise when converting gas turbine combustion chambers to hydrogen-containing fuels and pure hydrogen is the potential possibility of flashback into the fuel-air mixture preparation zone. This problem can be solved most simply by using the well-known principle of diffusion fuel combustion when separated flows of fuel and oxidizer are injected into the chemical reaction zone. But such combustion chambers have a significant drawback, determined by the high emission of nitrogen oxides in the main operating modes of a gas turbine engine.

The novelty of the proposed technical solution is the combination of (a) the principle of diffusion combustion of fuel with separate supply of components, which provides a sharp decrease in the probability of flashback zone formation when using hydrogen-containing gases and hydrogen and (b) the principle of operation of a combustion chamber of the "Aquarius" type gas turbine unit with a two-stage sequential injection of superheated steam to a chamber. Note that the first part of this steam is injected into the primary zone of a combustion chamber to reduce the combustion temperature of hydrogen-containing mixtures, suppress the formation of nitrogen oxides, and further suppress the possibility of a flashback zone. Let's call this part the steam ecological, because diluting the combustible mixture with this steam in the primary zone of the gas turbine combustion chamber leads to a decrease in the rate of formation of the main environmentally harmful pollutant-nitrogen oxides according to the Zeldovich thermal mechanism. The second part (energy steam) is separately injected into the dilution zone of a combustion chamber to increase the mass flow rate of the working media and raise specific engine power. Thanks to this proposed distribution of steam flows, it is possible to ensure stable combustion of various fuel-air mixtures in a wide range of changes in their physicochemical properties.

The article aims to investigate the energy and ecological characteristics of a combustion chamber of the "Aquarius" type gas turbine unit with steam injection operating on hydrogen-containing mixtures and hydrogen, as well as to determine the operating modes that ensure stable combustion of fuel without the formation of flashback zones.

2. Object of Investigation

A combustion chamber of a 16 MW "Aquarius" type gas turbine unit [2, 13], which is a cannular diffusion chamber (Figure 1) with 10 flame tubes, was chosen as the object of research. The main feature of this design is the injection of ecological steam into the primary combustion zone and energy steam into the dilution zone, which makes it possible to increase the specific power of the engine and significantly improve its environmental performance.

The injection of ecological steam to the region of the axial type vane swirler contributes to its good mixing with the working fluid in the primary (combustion) zone of a combustion chamber, lowering the maximum combustion temperature and suppressing the formation of nitrogen oxides in the flame tube. The injection of energy steam through a separate pipeline and an annular slot in the area of the flame tube mixer ensures an increase in the mass flow rate of the working fluid through a combustion chamber and the engine turbine part, as well as cooling the combustion products before being fed into the high-pressure turbine (in addition to air cooling). It is to be noted that the superheated steam is generated in the heat recovery steam generator, which is mounted at the outlet of the gas turbine engine.

The serial combustion chamber is used to burn natural gas. It is supposed to be modified for burning mixtures of hydrogen-containing gases and pure hydrogen within the framework of promising projects for the creation of decarbonized energy systems, including those for FPSO vessels and stationary power systems.

3. Mathematical Modeling

The modeling of physical and chemical processes in a combustion chamber of a gas turbine unit of the "Aquarius" type is based on the solution of differential equations of mass, impulse, and energy conservation for the multicomponent, turbulent, and chemically reacting system in the following way [14–16]:

(i) The mass conservation equation,

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{v}) = S_m. \tag{1}$$

(ii) The momentum conservation equation,

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla(\rho \vec{v}\vec{v}) = -\nabla p + \nabla \tau_{st} + \rho \vec{g} + \vec{F}. \tag{2}$$

(iii) The continuity equation for species,

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla(\rho \vec{v} Y_i) = -\nabla \vec{J}_i + R_i + S_i. \tag{3}$$

(iv) The internal energy equation,

$$\frac{\partial}{\partial t}(\rho E) + \nabla(\vec{v}(\rho E + p)) = -\nabla \vec{J}_i + S_h. \tag{4}$$

(v) The turbulent kinetic energy transport equation,

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) + \frac{\partial}{\partial x_j}\left[\left(\alpha_k \mu_{eff}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k. \tag{5}$$

(vi) The dissipation rate of the turbulent kinetic energy transport equation,

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) + \frac{\partial}{\partial x_j}\left[\left(\alpha_\varepsilon \mu_{eff}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon, \tag{6}$$

$$\begin{aligned}
\mu_{t0} &= \frac{C_\mu \rho k^2}{\varepsilon},\\
\mu_t &= \mu_{t0} f\left(\alpha_s, \Omega, \frac{k}{\varepsilon}\right),\\
R_\varepsilon &= \frac{C_\mu \rho \eta^3 (1 - (\eta/\eta_0))}{1 + \beta\eta^3}\frac{\varepsilon^2}{k},\\
\eta &= \frac{Sk}{\varepsilon}.
\end{aligned} \tag{7}$$

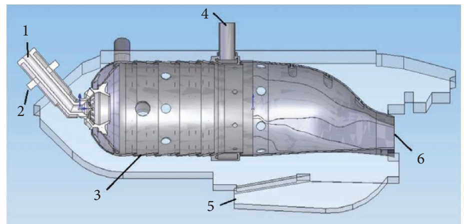

Figure 1: Combustion chamber of the "Aquarius" type gas turbine unit with steam injection: 1-fuel supply; 2-ecological steam injection; 3-flame tube; 4-energy steam injection; 5-air supply after the high-pressure compressor; 6-gas outlet to the turbine.

Table 1: Mechanism of fuel oxidation.

	Reaction	A	E (J/kg mole)	β	Reaction order			
1	$2\ CH_4 + 3\ O_2 \longrightarrow 2\ CO + 4\ H_2O$	$5.012e+11$	$2e-08$	0	CH_4	0.7	O_2	0.8
	$2\ CO + O_2 \longrightarrow 2\ CO_2$	$2.239e+12$	$1.7e+08$	0	O_2	0.25	CO	1.0
2	$2\ CH_4 + 3\ O_2 \longrightarrow 2\ CO + 4\ H_2O$	4.64e + 09	1.17e + 08	−0.062	CH_4	0.5	O_2	1.066
	$2\ CO + O_2 \longrightarrow 2\ CO_2$	3.97e + 11	7.68e + 07	0.215	O_2	1.756	CO	1.258
	$2\ CO_2 \longrightarrow 2\ CO + O_2$	6.02e + 05	1.31e + 08	−0.108	CO_2	1.357		
3	$2\ H_2 + O_2 \longrightarrow 2\ H_2O$	$9.87e+08$	$3.1e+07$	0	H_2	1.0	O_2	1.0

In most cases, for aerodynamic prediction, the RNG-based k-ε-turbulence model was used [17, 18]. In these equations, t is the time, ρ is the mass density of mixture, S_m is the mass added to the continuous phase from the dispersed second phase and any user-defined sources, p is fluid pressure, τ_{st} is a stress tensor, $\vec{g}$ and $\vec{F}$ are the gravitational and external body forces, respectively, Y_i, R_i are the mass fraction and net rate of production of species i by chemical reaction, respectively, $\vec{J}_i$ is the diffusion flux of species i, S_i is the rate of creation by addition from the dispersed phase plus any other source, S_h is the heat of chemical reaction, k and ε are the turbulent kinetic energy and the rate of its dissipation, respectively, u_i is the velocity components, μ_{eff} is the effective viscosity, G_k represents generation of the turbulence kinetic energy due to the mean velocity gradients, G_b is the generation of turbulence kinetic energy due to the buoyancy, Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, the quantities α_k and α_ε are the inverse effective Prandtl numbers for k and ε, respectively, S_k and S_ε are the user-defined source terms, $C_{1\varepsilon}$, $C_{2\varepsilon}$, and $C_{3\varepsilon}$ are the constants of the turbulence model, μ_{t0} is the value of the turbulent viscosity calculated without a swirl modification, Ω is the characteristic swirl number, α_s is the swirl constant, and β, S are the empirical constants.

The eddy-dissipation-concept (EDC) combustion model [19] was used to determine the energy and environmental characteristics of the combustion chamber with steam injection. This model assumes that reaction occurs in small turbulent structures, called fine scales. Species react in fine structures over a timescale. Reactions proceed over the timescale, governed by Arrhenius rates and are integrated numerically using the special ISAT algorithm. So, to calculate the net source of species by chemical reaction, it is necessary to find the volume fine scale and time scale. The length fraction and time scales are

$$\begin{aligned} \xi^* &= C_\xi \left(\frac{\nu\varepsilon}{k^2}\right)^{(1/4)}, \\ C_\xi &= 2.1377, \\ \tau^* &= C_\tau \left(\frac{\nu}{\varepsilon}\right)^{(1/2)}, \\ C_\tau &= 0.4082, \end{aligned} \tag{8}$$

where ξ^* is the size of a small-scale reactor which depends on the kinematic viscosity ν, the turbulence kinetic energy k, and the dissipation rate of the turbulence kinetic energy ε, C_ξ and C_τ are the constants, and τ^* is the time within which a reaction takes place.

For the prediction of the CO emission global, two-step mechanism of methane oxidation was used as well as its modification with an additional third reaction for the CO_2 decomposition. To determine the hydrogen burnout in a combustion chamber, a single-stage global oxidation reaction was used. Arrhenius equations were used to calculate reaction rate constants for all reactions. Necessary values for the reaction rates calculation are shown in Table 1.

Presented kinetic mechanisms are included in the mathematical model of the 3-D reacting flow for the numerical experiments with the implementation of the CFD complex ANSYS Fluent [20].

The following equation was used to determine the concentrations of nitrogen oxides in a combustion chamber [21]:

$$\frac{\partial}{\partial t}\left(\rho Y_{NO}\right) + \nabla \cdot \left(\rho \vec{v} Y_{NO}\right) = \nabla \cdot \left(\rho D \nabla Y_{NO}\right) + S_{NO}, \tag{9}$$

where Y_{NO} is the NO mass concentration, D is the diffusion coefficient, $\vec{v}$ is the velocity vector, and S_{NO} is the source term depending on the NO_x formation (destruction) mechanism.

The numerical solution of the system of equations (1)–(9) was carried out by the finite-difference method described in [19]. Typical root mean square residuals to establish the solution convergence are about $1e-4$.

To verify the mathematical model of a combustion chamber with the sequential injection of ecological and energy steam, the appropriate tests were carried out at the "Zorja"-"Mashpoekt" Gas Turbine Research & Production Complex [2, 22]. The experiments were carried out on the "Aquarius" type gas-steam turbine unit under bench conditions. Unit parameters at nominal operating mode are power 16 MW, natural gas flow rate 2775 kg/h, air flow rate through a combustion chamber 32.9 kg/s, air temperature at the inlet of a combustion chamber 713 K, total steam flow rate 5.256 kg/s, steam temperature 583 K, and total air pressure behind the compressor 1.883 MPa. The parameters of a gas turbine combustion chamber are shown in Table 2 for nine engine operating modes. It should be noted that at the beginning, the operating modes only with the injection of energy steam into a combustion chamber were investigated and then with the combined injection of ecological and energy steam.

To take into consideration, the influence of the number of nodes of the finite-difference mesh of the 1/10th part of the combustion chamber of the "Aquarius" type on the workflow parameters and preliminary calculations were carried out on a "rare" mesh consisting of 1.8 million tetrahedrons and a "dense" mesh consisting of 4.5 million tetrahedrons. At the same time, the surface meshes for the corresponding modifications remained unchanged.

As a criterion for comparing the efficiency of the calculation procedure, the total pressure losses inside the combustion chamber were taken, which were also determined experimentally. At the nominal operation mode of the combustion chamber working on natural gas, the total pressure loss, measured experimentally, was 5.8%. When using the RNG k-ε and standard k-ε turbulence models, the total pressure loss for the "rare" mesh was 3.68% and 3.05%, and 5.7% and 4.9% for the "dense" mess, respectively. It is to be noted that in all cases, the deviation of the calculated average temperature in the outlet section of the combustion chamber did not differ from the experimentally determined (1374 K) one by more than 0.9%. Thus, further in all calculations, the "dense" grid shown in Figure 2 and the RNG k-ε turbulence model were used.

Three-dimensional calculations were carried out using the kinetic schemes presented in Table 1. A comparison of the calculation results for the proposed model and experimental data is shown in Figures 3 and 4.

Dependencies between the carbon dioxide concentrations at the outlet of a combustion chamber and the relative gas turbine unit power $\overline{N}_e$ are shown in Figure 3. It can be seen that the three-stage mechanism 2 (Table 1) gives a much better agreement between the experimental and calculated data on CO_2 concentrations, which can generally be considered satisfactory. Further calculations of the energy and ecological parameters of a combustion chamber with steam injection were carried out for this particular kinetic mechanism. It should be noted that the greatest discrepancies occur at partial operating modes of the power plant.

Diagrams of the exit NO_x emission depending on the relative unit power $\overline{N}_e$ (Figure 4) were built as the results of the numerical and full-scale tests. The difference between the calculations and the experimental data can be seen only for the operating modes with energy steam injection. The usage of investigated mechanisms gives good agreement with experimental data for the operating modes with ecological and energy steam injection. That is very important because these modes are basic ones for the gas-and-steam turbine unit.

The dependence of the mass concentrations of carbon monoxide CO in the combustion chamber's outlet section on the ratio of the total steam (ecological and energy) consumption to the flow rate of gaseous fuel $G_{\text{steam}}/G_{\text{fuel}}$ is shown in Figure 5. There is a good correlation between experimental and calculated data.

The presented data indicate the potential of the mathematical model used to predict the energy and ecological characteristics of diffusion-type gas turbine combustion chambers with steam injection in a wide range of operating modes. Some discrepancy between the calculated and experimental data is explained by the complexity of the mixing and reaction processes under conditions of intense turbulence and swirling flows. The direction of future research is the application of promising methods of numerical analysis, such as large eddy simulation [23].

4. Results and Discussion

To calculate the characteristics of the working process in a promising combustion chamber of the "Aquarius" gas-steam turbine unit, the corresponding three-dimensional calculations were carried out using the Ansys Fluent computer complex. When calculating the working process of the combustion chamber operating on natural gas, hydrogen-containing mixtures, and pure hydrogen, the following boundary conditions were used:

(i) For fuel supply 1 (Figure 1), the mass flow rate is 0.07366 kg/s (when operating on natural gas) and changes with hydrogen additions in proportion to the change in the net calorific value occur, with fuel temperature 300 K;

(ii) For ecological steam injection 2, the mass flow rate varies, with steam temperature 700 K;

(iii) For energy steam injection 4, the mass flow rate varies, with steam temperature 700 K;

(iv) For air supply 6, the mass flow rate is 2.752 kg/s, air temperature is 769.3 K, and air pressure is 2.383 MPa;

(v) For gas outlet 6, it is pressure outlet.

Note that the total flow rate of steam injected into the combustion chamber did not change and was equal to 0.455 kg/s.

Table 2: Operating parameters of a gas turbine combustion chamber.

Relative power	Energy steam flow rate (kg/s)	Ecological steam flow rate (kg/s)
0.265	2.130	0
0.425	2.869	0
0.485	3.141	0
0.486	3.150	0
0.487	2.566	0.558
0.589	2.819	0.703
0.740	3.152	0.828
0.866	3.563	0.858
0.868	3.606	0.774

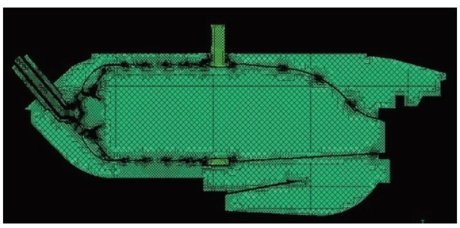

Figure 2: Mesh model of the combustion chamber.

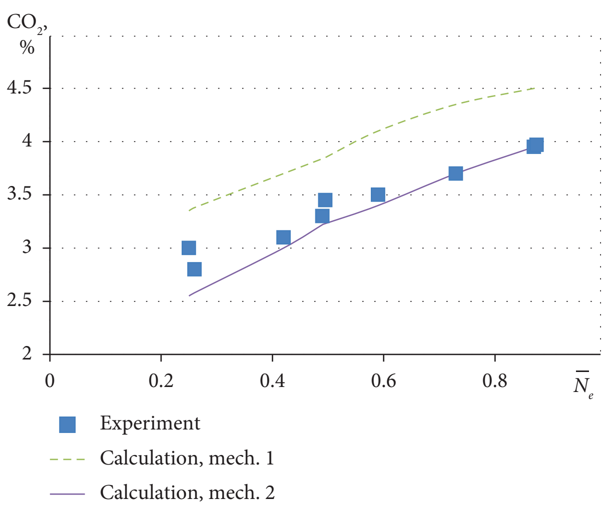

Figure 3: Calculated and measured CO_2 concentrations: ▪-experiment; — — —-calculation (mechanism 1); —-calculation (mechanism 2).

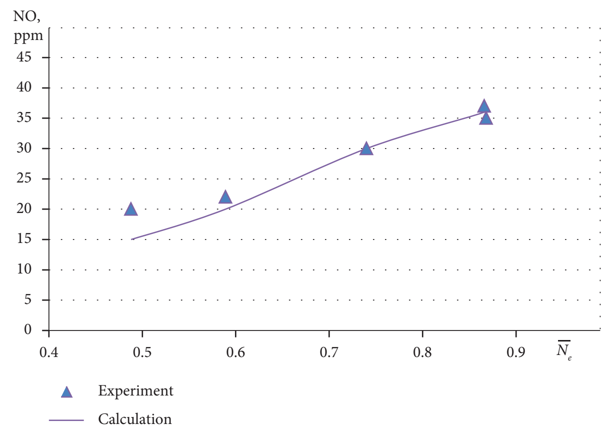

Figure 4: Comparison of experimental and calculated emission of nitrogen oxides.

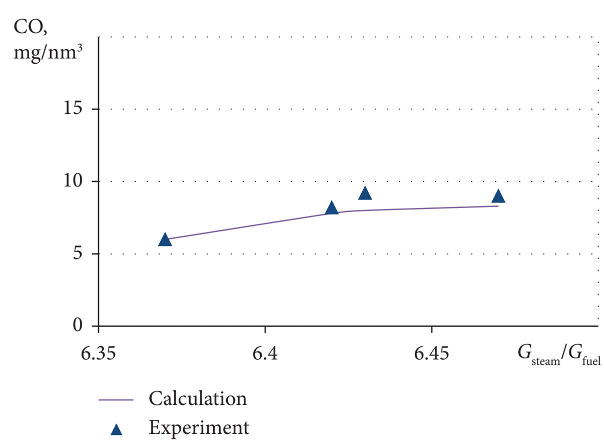

Figure 5: Comparison of experimental and calculated concentrations of carbon monoxides.

Natural gas (a mixture of natural gas with hydrogen or pure hydrogen) was supplied to the central channel of the burner device (Figure 1) and then was directed to the primary zone of a combustion chamber through a system of holes in the head of the burner device. The air after the high-pressure compressor entered a combustion chamber diffuser and was further distributed in the annular gap between combustion chamber housings (outer and inner) and the flame tubes and then was directed through the holes into the flame tubes. Passing through the vane swirler of the flame tube front device, the air swirled. Due to this, a stable recirculation zone, as in [24], was formed in the paraxial region of the flame tube, in which hot combustion products are located. Due to the presence of this zone, reliable ignition of new portions of fuel and stabilization of combustion processes of fuel-air mixtures is carried out in a wide range of changes in fuel, air, and ecological steam flow rate. Such a scheme for feeding reagents makes it possible to organize the diffusion mode of combustion and practically eliminate the possibility of a flashback inside the burner. The feeding of

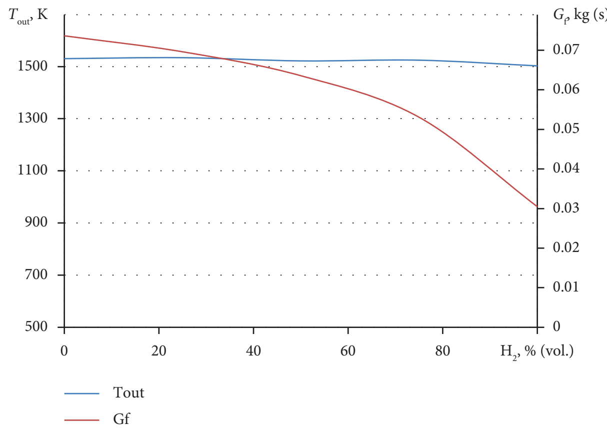

Figure 6: Dependences of gas temperature at the combustion chamber's outlet and fuel mass flow rate on the volume content of hydrogen in the mixture.

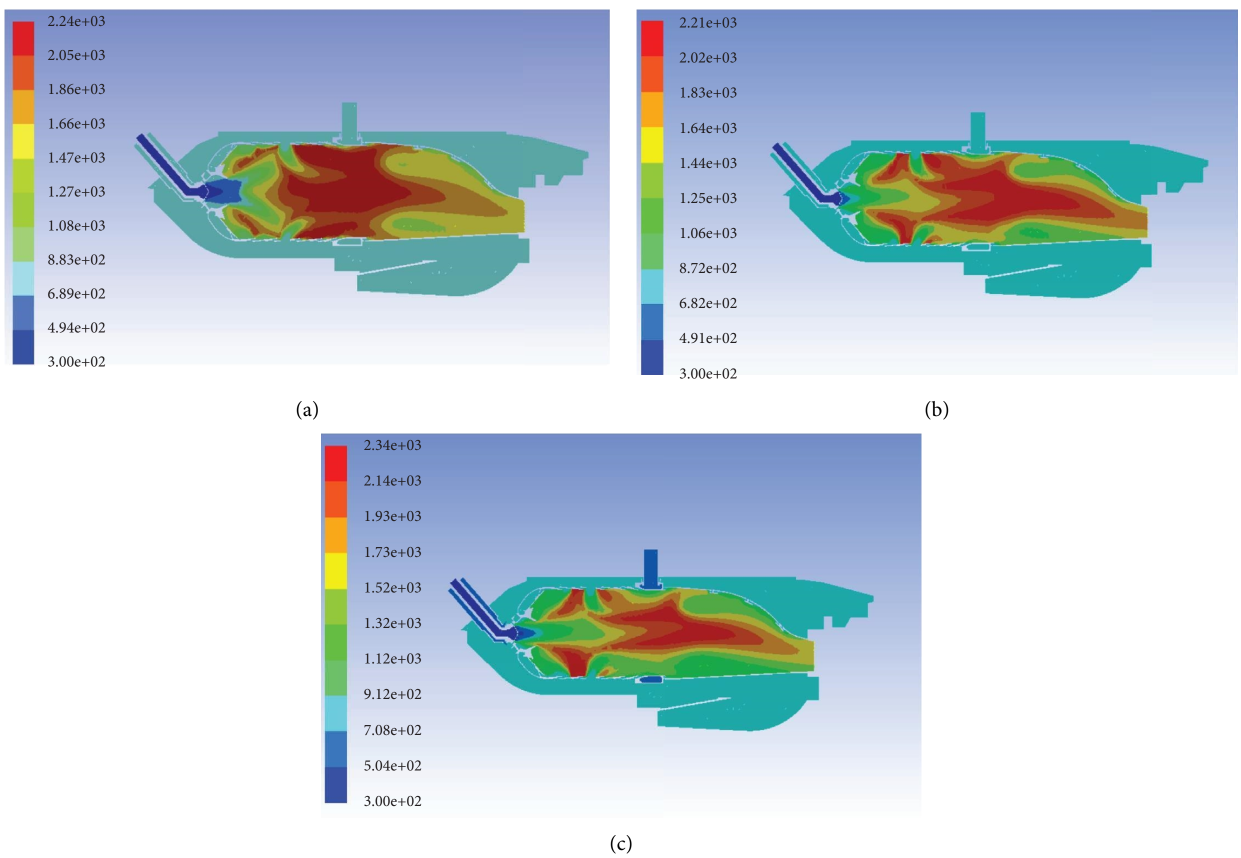

Figure 7: Contours of temperature (K), inside a combustion chamber for different volume content of hydrogen in the mixture: 0 (a), 50% (b), 100% (c).

ecological steam is carried out through a separate pipeline in the area of the vane swirler. This steam is premixed with the air entering through the swirler blade and contributes to a decrease in the combustion temperature and a sharp decrease in the formation of thermal nitrogen oxides. The second part of the steam (energy steam) is fed through a separate pipeline and injected through special openings in the flame tubes in the area of the dilution zone of a combustion chamber to increase the mass flow rate of the working fluid. Subsequently, the resulting gas-steam mixture is directed to the engine's high-pressure turbine to perform work.

Figure 6 shows graphs of gas temperature at the outlet of a combustion chamber T_{out} and fuel mass flow rate G_f on the volume content of hydrogen in a mixture with natural gas for one flame tube.

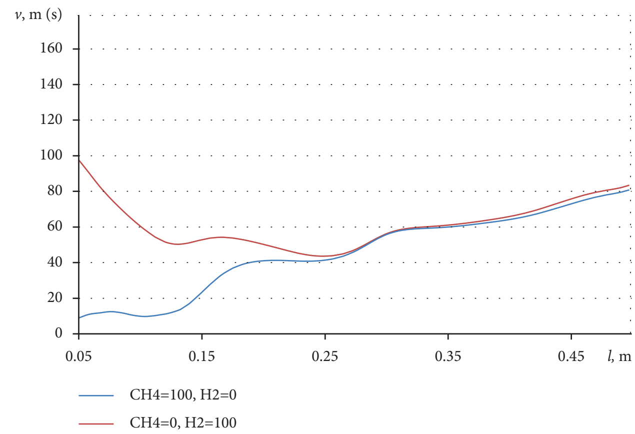

Figure 8: Change in the working fluid velocity along the flame tube axis with a hydrogen content of 0 and 100%.

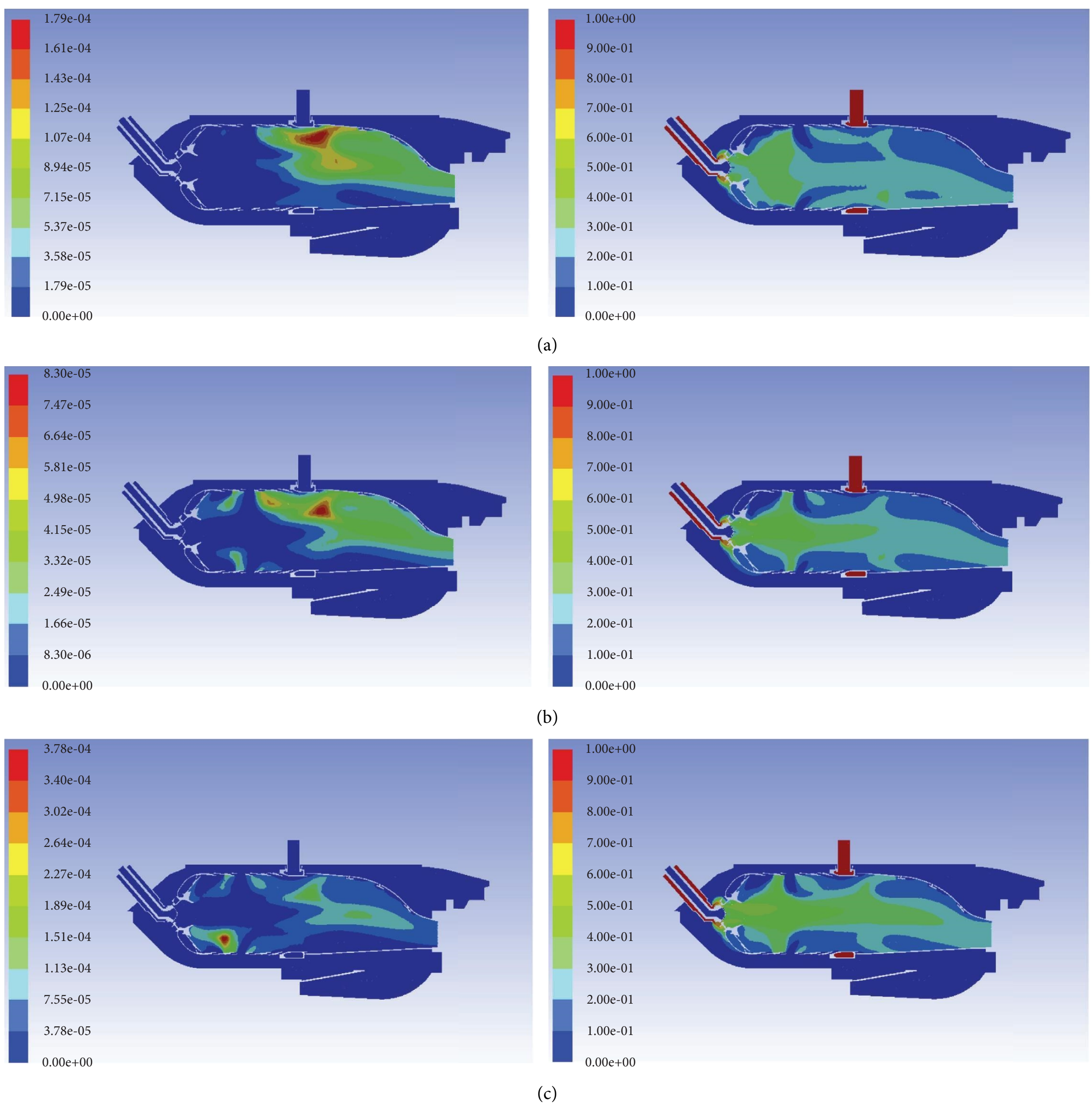

Figure 9: Contours of mass fraction of NO and H_2O inside the combustion chamber for different volume content of hydrogen in the mixture: 0% (a), 50% (b), 100% (c).

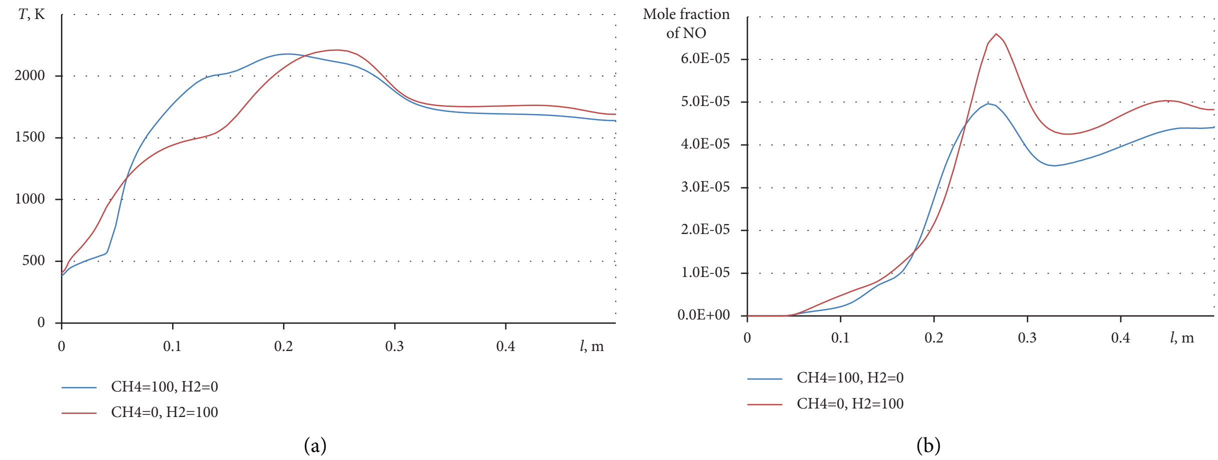

Figure 10: Dependences of temperature (a) and NO mole fraction (b) along the flame tube axis at 0 and 100% hydrogen content in the mixture.

It should be noted that the decrease in fuel flow rate was calculated in proportion to the increase in the net calorific value of the fuel mixture with an increase in the amount of hydrogen. The average gas temperature at the outlet of a combustion chamber was maintained at about 1523 K (Figure 6) and remained almost constant with a change in the amount of hydrogen in the mixture.

The temperature distribution in the longitudinal section of a combustion chamber with a change in the hydrogen volume content in the mixture from 0 to 100% is shown in Figure 7. One can see some change in the structure of the burning fuel flame with the concentration of zones of high temperatures in the axial sections of the flame tube. This is due to an increase in the fuel flow velocity with an increase in the hydrogen content in the mixture due to its lower density.

This is confirmed by the graphic dependences of the working fluid velocity v along the flame tube axis length l when the hydrogen content changes from 0 to 100% (by volume) in the mixture (Figure 8). Closer to the outlet sections of the flame tube, the velocities of the working fluid are aligned, because the average temperatures of the combustion products at the outlet are maintained constant, independent of the type of fuel.

The distribution of mass fractions of nitrogen oxide NO and steam H_2O in the longitudinal section of a combustion chamber with a change in the hydrogen content in the mixture from 0 to 100% is shown in Figure 9.

It can be seen that when pure hydrogen is burned, the mass fractions of nitrogen oxide are the largest, which is determined by the change in the heat release curve inside a combustion chamber. In this case, the zone of maximum nitrogen oxide concentrations moves to the flame tube front part, which determines higher nitrogen oxide emission at the outlet of a combustion chamber. When pure hydrogen is burned, more water vapors are formed and their total volume in the flame tube also increases.

Figure 10 shows the dependences of the temperature and the mole fraction of nitrogen oxides NO along the flame tube axis with a change in the hydrogen content from 0 to 100% (by volume) in the mixture. With an increase in the hydrogen content from 0% (natural gas) to 100% (pure hydrogen), the nature of the heat release curve along the length of the flame tube is transformed in such a way that the content of nitrogen oxides in cross-sections close to the outlet increases.

However, this trend is violated at hydrogen contents in the mixture (by volume) of 25, 50, and 75%. This is evidenced by the contours of the mass fractions of nitrogen oxides NO in the flame tube outlet section for five different values of the hydrogen content in the mixture (Figure 11), as well as the distribution of average NO emissions at the outlet of a combustion chamber (Figure 12).

As expected, carbon monoxide emission with an increase in the hydrogen content in the mixture constantly falls and reaches zero values when pure hydrogen is burned (Figure 10). This is due to the intensification of combustion of the main fuel-air mixture, some increase in the maximum combustion temperature inside the chamber's volume reduces the total carbon content in the mixture. When the hydrogen content changes from 0 to 50%, nitrogen oxide emission initially decreases from 36.1 to 17.8 ppm due to a decrease in the oxygen concentration during fuel combustion intensification and the corresponding rise of steam feeding to the primary zone. Furthermore, the amount of nitrogen oxides rises to 38 ppm when operating on pure hydrogen as the result of an increase in the peak temperatures of the working fluid.

In all cases, for the investigated operating modes, the calculated CO content at the combustion chamber outlet does not exceed 18.1 ppm, which corresponds to the European requirements for emission from gas turbine engines [24]. When the hydrogen content in the mixture is from 25 to 75%, the calculated emission of nitrogen oxide NO does not exceed 20.7 ppm, which also meets the requirements of [25]. Some excess nitrogen oxide emissions when operating on pure hydrogen can be compensated by the redistribution of the amount of ecological and energy steam injected

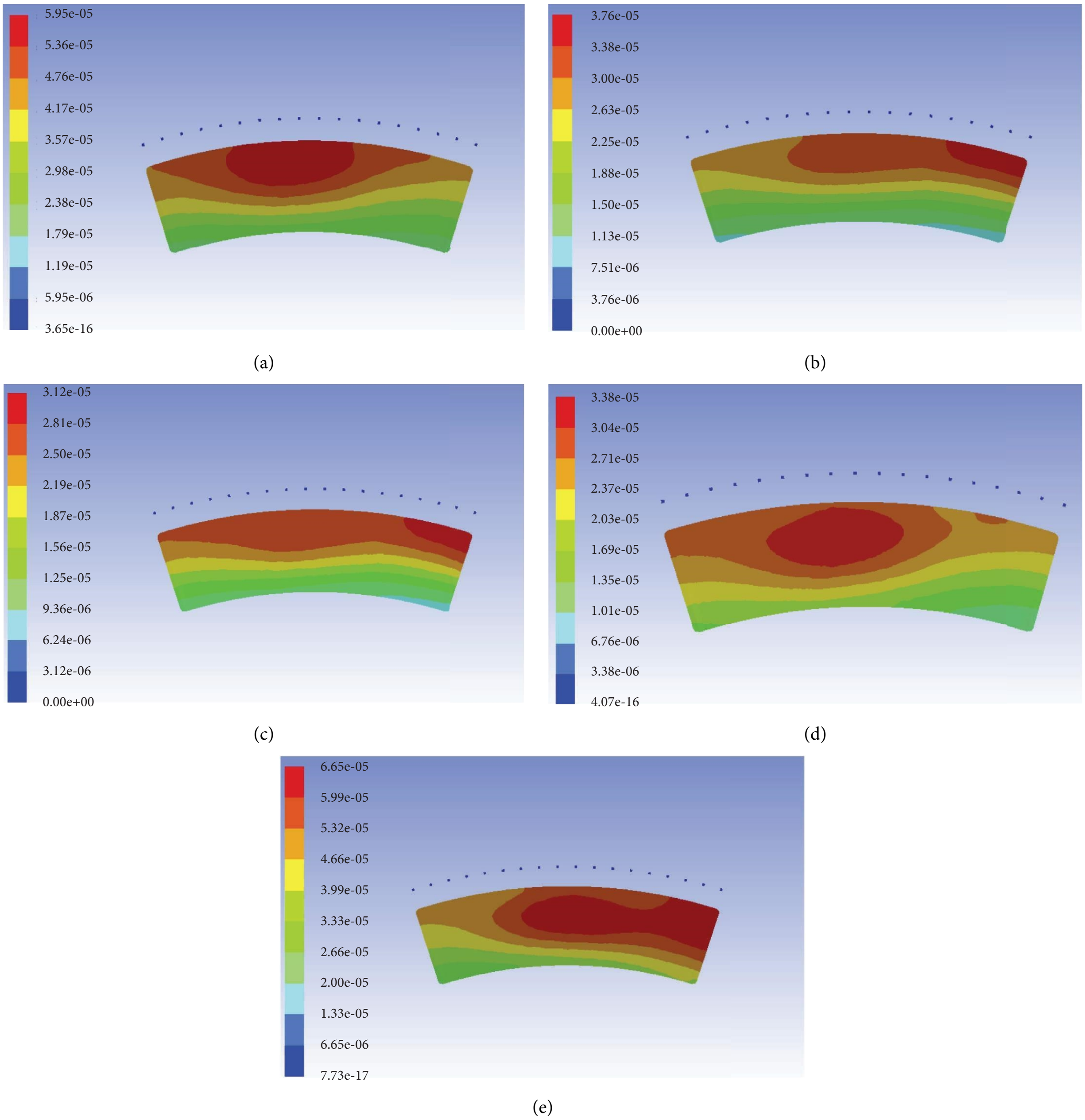

Figure 11: Contours of mass fraction of NO at the outlet section of a combustion chamber for different volume content of hydrogen in the mixture: 0% (a), 25% (b), 50% (c), 75% (d), and 100% (e).

into a combustion chamber, which requires additional studies.

Another unfavorable moment that occurs when a combustion chamber of the considered design is converted from natural gas to hydrogen is an increase in the nonuniformity of the temperature field at the flame tube outlet. Figure 13 shows the dependence of the coefficient of the overall nonuniformity of the temperature field at the outlet of a combustion chamber δ on the hydrogen content in the mixture.

It should be noted that the coefficient of the overall temperature nonuniformity was determined by the following formula:

$$\delta = \frac{T_{\max} - T_{av}}{T_{\max}}, \qquad (10)$$

where $T_{\max}$ and T_{av} are the maximum and average temperatures at the flame tube outlet, respectively.

With an increase in the hydrogen content in the mixture from 0 to 100%, the coefficient of the overall nonuniformity of the temperature field increases from 6.74 to 13.64%. This is explained by an increase in the fuel velocity at the burner outlet in the axial sections of the flame tube during the transition from natural gas to pure hydrogen. This undesirable phenomenon can be eliminated by changing the

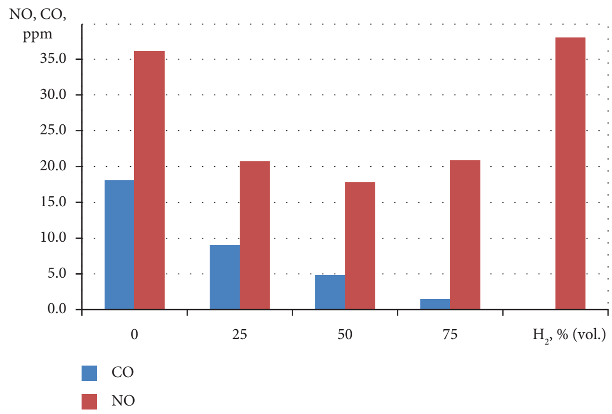

Figure 12: Distribution of mole fractions of NO and CO at the flame tube outlet for different volume content of hydrogen in the mixture.

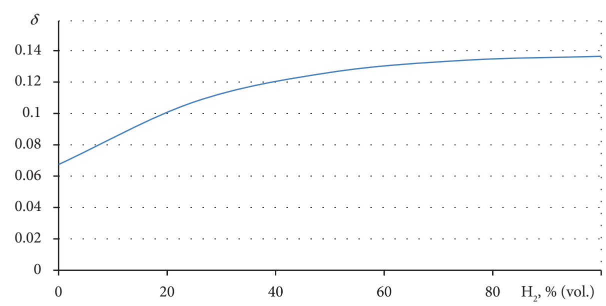

Figure 13: Dependence of the overall nonuniformity of the temperature field at the combustion chamber's outlet for different volume content of hydrogen in the mixture.

distribution of secondary air in the region of the flame tube mixer and by modifying the geometry of the mixer itself.

It should be noted that for all the investigated operating modes, no flashback zones were observed in the volume of the burner device, which once again confirms the advantages of the diffusion scheme of fuel combustion.

5. Conclusions

To determine the effect of the hydrogen content in a mixture with natural gas on the energy and emission characteristics of a gas turbine combustion chamber with steam injection, the three-dimensional CDF design method was used. For the first time, a technical solution has been proposed that combines the principle of diffusion combustion of fuel and the organization of the operation of a combustion chamber of gas turbine plants of the "Aquarius" type with a two-stage sequential injection of superheated steam to a chamber. Ecological steam is injected into the primary zone of a combustion chamber to suppress the formation of nitrogen oxides and reduce the maximum combustion temperature of hydrogen-containing fuel, and energy steam is separately injected into the dilution zone of a combustion chamber to increase the mass flow rate of the working mixture.

An increase in the hydrogen content in the mixture for the investigated combustion chamber with the separate injection of ecological and energy steam leads to a decrease in carbon monoxide CO emission due to the intensification of the combustion of the fuel-air mixture in the primary zone of a combustion chamber and reducing the total carbon content in the mixture. For the investigated chamber's operating modes, CO emission does not exceed 18.1 ppm, which corresponds to modern European requirements for emissions from gas turbine engines. Emissions of nitrogen oxide NO when the hydrogen content changes from 0 to 50% initially decrease from 36.1 to 17.8 ppm due to increased steam injection to the primary zone; and then increase to 38 ppm when operating on pure hydrogen. Further work is required to redistribute the flow rates of ecological and energy steam injected to a combustion chamber to minimize emission.

For all the investigated modes of operation of a combustion chamber with sequential steam injection, the formation of flashback zones in the volume of the burner device was not observed, which once again confirms the advantages of the chosen diffusion scheme of fuel combustion.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The article was written in the framework of promising, unfunded research of the Admiral Makarov National University of Shipbuilding, Ukraine.

References

[1] D. Y. Cheng and A. L. C. Nelson, "The Chronological Development of the Cheng Cycle Steam Injected Gas Turbine during the Past 25 Years," in *Proceedings of the ASME Turbo Expo 2002*, pp. 1–8, Amsterdam, the Netherlands, June 2002.

[2] S. N. Movchan, V. V. Romanov, V. N. Chobenko, and A. P. Shevtsov, "Contact steam-and-gas turbine units of the "AQUARIUS" type: the present status and future prospects," in *Proceedings of the ASME turbo expo 2009: Power for Land, Sea, and Air*, Orlando, FL, USA, June 2009.

[3] I. B. Matveev, S. I. Serbin, and N. V. Waschilenko, "Plasma-assisted treatment of sewage sludge," *IEEE Transactions on Plasma Science*, vol. 44, no. 12, pp. 3023–3027, 2016.

[4] J. Beita, M. Talibi, S. Sadasivuni, and R. Balachandran, "Thermoacoustic instability considerations for high hydrogen combustion in lean premixed gas turbine combustors: a review," *Hydro*, vol. 2, no. 1, pp. 33–57, 2021.

[5] N. Tekin, M. Ashikaga, A. Horikawa, and H. Funke, "Enhancement of fuel flexibility of industrial gas turbines by development of innovative hydrogen combustion systems," *Gas for energy*, vol. 2, 2018.

[6] A. Cappelletti, F. Martelli, E. Bianchi, and E. Trifoni, "Numerical redesign of 100kw MGT combustor for 100% H2 fueling," *Energy Procedia*, vol. 45, pp. 1412–1421, 2014.

[7] A. H. Ayed, K. Kusterer, H. H. W. Funke, J. Keinz, and D. Bohn, "CFD based exploration of the dry-low-NOx hydrogen

micromix combustion technology at increased energy densities," *Propulsion and Power Research*, vol. 6, no. 1, pp. 15–24, 2017.

[8] S. Sayed Reza, M. Rahimi, A. Khoshhal, and A. A. Alsairafi, "CFD study on hydrogen-air premixed combustion in a Micro scale chamber," *Iranian journal of chemistry and chemical engineering*, vol. 29, no. 4, pp. 161–172, 2010.

[9] P. Gobbato, M. Masi, A. Toffolo, and A. Lazzaretto, "Numerical simulation of a hydrogen fuelled gas turbine combustor," *International Journal of Hydrogen Energy*, vol. 36, no. 13, pp. 7993–8002, 2011.

[10] M. E. Hadi Attia, A. Khechekhouche, and Z. Driss, "Numerical simulation of methane-hydrogen combustion in the air: influence on combustion parameters," *Indian Journal of Science and Technology*, vol. 11, no. 2, pp. 1–8, 2018.

[11] N. Syred, M. Abdulsada, A. Griffiths, T. O'Doherty, and P. Bowen, "The effect of hydrogen containing fuel blends upon flashback in swirl burners," *Applied Energy*, vol. 89, no. 1, pp. 106–110, 2012.

[12] S. Göke, M. Füri, G. Bourque et al., "Influence of steam dilution on the combustion of natural gas and hydrogen in premixed and rich-quench-lean combustors," *Fuel Processing Technology*, vol. 107, pp. 14–22, 2013.

[13] S. Serbin, A. Mostipanenko, and I. Matveev, "Investigation of the working processes in a gas turbine combustor with steam injection," in *Proceedings of the ASME/JSME 8th Thermal Engineering Joint Conference*, pp. 1–6, Honolulu, Hawaii, March 2011.

[14] I. B. Matveev, S. I. Serbin, V. V. Vilkul, and N. A. Goncharova, "Synthesis gas afterburner based on an injector type plasma-assisted combustion system," *IEEE Transactions on Plasma Science*, vol. 43, no. 12, pp. 3974–3978, 2015.

[15] S. I. Serbin, A. V. Kozlovskyi, and K. S. Burunsuz, "Investigations of non-stationary processes in low emissive gas turbine combustor with plasma assistance," *IEEE Transactions on Plasma Science*, vol. 44, no. 12, pp. 2960–2964, 2016.

[16] BE. Launder and D. B. Spalding, *Lectures in Mathematical Models of Turbulence*, Academic Press, London, UK, 1972.

[17] D. Choudhury, "Introduction to the renormalization group method and turbulence modeling," Fluent inc, Washington, D.C, USA, Technical Memorandum TM-107, 1993.

[18] S. I. Serbin, "Features of liquid-fuel plasma-chemical gasification for diesel engines," *IEEE Transactions on Plasma Science*, vol. 34, no. 6, pp. 2488–2496, 2006.

[19] R. Meloni, "Pollutant emission validation of a heavy-duty gas turbine burner by CFD modeling," *Machines*, vol. 1, no. 3, pp. 81–97, 2013.

[20] ANSYS, *ANSYS Fluent Theory Guide*, ANSYS, Inc, 2013.

[21] O. Cherednichenko, S. Serbin, and M. Dzida, "Application of thermo-chemical technologies for conversion of associated gas in diesel-gas turbine installations for oil and gas floating units," *Polish Maritime Research*, vol. 26, no. 3, pp. 181–187, 2019.

[22] S. Serbin and K. Burunsuz, "Numerical study of the parameters of a gas turbine combustion chamber with steam injection operating on distillate fuel," *International Journal of Turbo and Jet Engines*, 2020.

[23] J. Smagorinsky, "General circulation experiments with the primitive equations," *Monthly Weather Review*, vol. 91, no. 3, pp. 99–164, 1963.

[24] I. B. Matveev and S. I. Serbin, "Theoretical and experimental investigations of the plasma-assisted combustion and reformation system," *IEEE Transactions on Plasma Science*, vol. 38, no. 12, pp. 3306–3312, 2010.

[25] Official Journal of the European Union, "Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on Industrial Emissions (Integrated Pollution Prevention and Control)," 2010, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32010L0075.