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Three-Dimensional Analysis of a Steam-Injected Gas Turbine Combustor Fuelled by an Ammonia-Hydrogen Blend

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ABSTRACT

This work presents a 3D numerical study of a steam-injected combustor for a gas turbine operating on an ammonia-hydrogen fuel blend, aimed at enabling carbon-free hybrid energy systems. The research focuses on the performance and emission characteristics of a 32 MW engine's combustor. Using Computational Fluid Dynamics (CFD) with a detailed chemical kinetics mechanism (203 reactions, 31 species), the model solves the governing equations for turbulent reacting flow. The simulations provide new insights into ammonia-hydrogen flame propagation within intensely swirled flows under staged air and steam admission. Key energy and environmental parameters for the combustor are obtained. The results support the design of advanced combustors for decarbonised gas turbine systems.

Keywords: gas turbine engine, combustor, ammonia, hydrogen, hybrid energy systems

INTRODUCTION

Ammonia is recognised as a key alternative to traditional carbon-based fuels for gas turbine (GT) installations, particularly in marine power, aligning with global decarbonisation trends [1,2]. Its consideration as a future fuel is integral to the "green" hydrogen economy strategy, as ammonia serves as an effective hydrogen carrier. However, its physicochemical properties pose significant technical challenges [3-5]:

1. Low flame speed and narrow flammability limits necessitate radical modifications to classical combustion schemes to prevent pulsations and flameout, especially under low-load conditions.
2. This carbon-free fuel, due to its high bound nitrogen content, becomes a potential source of significant nitrogen oxide (NO_x) emissions, demanding innovative suppression methods without efficiency loss.
3. Leaks of unburned NH_3 are hazardous to personnel and the environment. Furthermore, ammonia can cause stress corrosion cracking in copper and its alloys and corrodes certain steels, restricting material choices for the fuel system.

To mitigate these drawbacks, various approaches are proposed [4,5]:

1. Using composite fuel blends, by adding hydrogen or natural gas to ammonia, to improve combustion performance and stabilise the process. Hydrogen doping not only enhances mixture reactivity but also enables combustion mechanisms aimed at reducing NO_x through the formation of intermediate radicals.
2. Implementing two-stage (multi-phase) combustion following a "rich-lean" mixture principle for NO_x control.
3. Alongside staged combustion, the use of micro-mixing and "Moderate" or "Intense" Low-oxygen Dilution (MILD) combustion effects looks promising. These techniques

suppress NO_x formation by promoting a more homogeneous temperature distribution.
4. Promising research has focused on catalytic pre-reformers for the partial decomposition of NH_3 into H_2 and the use of plasma discharges for active flame chemistry control.

The economic appeal of ammonia is not only driven by the absence of direct CO_2 emissions but, also, by a mature global infrastructure for its production, storage, and maritime transport, making it a practical candidate for rapid decarbonisation.

Recent research intensity indicates a transition from the conceptual justification of ammonia use to the technological engineering phase [6-8]. Beyond studying pure NH_3 combustion processes, significant attention has been paid to its integration into hybrid and combined cycles. One particularly promising direction is the implementation of cycles with steam injection (e.g. STIG or Cheng cycles), generated via waste heat recovery [9]. This technology simultaneously addresses several tasks: increasing specific power, improving engine control characteristics, and lowering flame temperature.

Crucially, steam not only acts as a working fluid but it also acts as an active thermochemical agent, participating in in-flame steam-reforming reactions in ammonia, promoting hydrogen formation, which, in some cases, can enhance flame stability. Optimal steam dosing can shift the chemical equilibrium in the reaction zone, minimising emissions of both NO_x (by reducing peak temperature) and unburned ammonia (by intensifying oxidation processes).

However, process heterogeneity, upon introducing a third agent (steam), creates new problems:

1. The excessive flame temperature reduction from excess steam leads to incomplete fuel oxidation and increased emissions of unburned ammonia and hydrazine (N_2H_4).
2. The control system must dynamically balance three independent flows (fuel, air, and steam) under variable loads, requiring novel control algorithms.
3. The risk of insufficient mixing quality leads to localised hot/cold zones and ineffective emission control.
4. Increased corrosiveness of the environment (mixture of high-temperature gases and steam), necessitating special resistant materials.
5. The potential formation of secondary harmful compounds, such as nitrous oxide (N_2O) or ammonium hydroxide (NH_4OH), under low-temperature or incomplete combustion conditions.
6. Dilution of the fuel-air mixture by steam reduces flame speed, decreases stability, and increases susceptibility to extinction in transient regimes.

Addressing this issue may involve adding fuels with high calorific values, such as hydrogen or natural gas, to the fuel-air mixture [10-12]. The study by Okafor et al. [13] investigated the laminar burning velocity of premixed CH_4–NH_3–air flames. The results showed how ammonia doping affects methane combustion kinetics, which is critical for understanding the behaviour of hybrid fuels ($NH_3/H_2/CH_4$) and optimising their combustion process in GT combustors. The research in [14] was dedicated to the practical application of ammonia in real combustors. The authors analysed the stability limits and NO_x emissions of swirled ammonia-methane-air flames, providing data on how ammonia doping affects flame stability and environmental performance under near-gas-turbine conditions.

Article [15] investigated the combustion of pure ammonia and its mixtures with hydrogen in a constant volume combustion chamber. The authors analysed pressure, burn rate, and emission characteristics. The work demonstrated that the addition of hydrogen significantly improves ammonia reactivity, which is crucial for GT applications. The study by [16] demonstrated the operation of a real gas turbine installation on ammonia and an ammonia-methane blend. The authors provided experimental data on efficiency, operational stability, and, most importantly, NO_x emissions.

Paper [17] was devoted to the numerical modelling of a gas-turbine-like combustor operating on a premixed ammonia/air mixture. The authors investigated the influence of combustor design (flow swirl, secondary air injection, etc.) on flame stability and NO_x formation, showing pathways towards designing optimised ammonia combustors. The work by [18] focused on a rich-lean combustion strategy for ammonia and hydrogen. Experiments on a swirled flame showed how stable combustion and NO_x emission control can be achieved by managing process staging. The research by [19] provided a detailed comparison of various Rich-Quench-Lean combustion concept variants for ammonia-hydrogen mixtures using numerical modelling. The authors evaluated the impact of different parameters (fuel ratio, dilution degree, etc.) on the emission of nitrogen oxides and the formation of unburned ammonia, offering recommendations for optimising the process in GTs.

Therefore, despite its significant potential, the widespread adoption of ammonia requires in-depth research, in order to overcome these barriers and ensure reliability and safety [13].

PROBLEM STATEMENT

Despite active research, questions regarding the synergistic influence of an NH_3/H_2 blend, combined with superheated steam injection, on the structure of turbulent reactive flow, pollutant generation/suppression mechanisms, and the dynamic flame stability in a real GT combustor remain insufficiently studied. There is a lack of experimentally validated data for complex kinetic models describing such multi-component processes.

The objective of this work is a three-dimensional investigation of the performance and emission characteristics of a steam-injected combustor, operating on an ammonia-hydrogen mixture. The research focuses on the working processes within the combustor of a 32 MW gas turbine engine running on an ammonia-hydrogen blend.

APPROACHES TO MODELLING

In the development of advanced energy systems based on gas turbine engines utilising carbon-neutral fuels, significant attention has been paid to the application of complex thermodynamic cycles, such as the Steam Injected Gas Turbine

(STIG), which enable enhanced utilisation of exhaust gas heat [21]. Similar to cogeneration systems, thermal energy from the engine exhaust gas is used to generate steam in a heat recovery steam generator. However, unlike traditional schemes, the generated steam is not used as a heat carrier but is directly supplied to the combustor and, subsequently, to the turbine flow path, acting as an additional working fluid and contributing to an increase in the plant's mechanical power.

To improve combustion efficiency under steam injection conditions, a special design scheme for the fuel-burning device was proposed [22]. This scheme provided for the division of steam into two functionally distinct streams: ecological and energetic. This approach allowed for the simultaneous optimisation of environmental performance and the energy efficiency of the combustor.

The combustor was designed as a reverse-flow tubular-annular (can-annular) type (Fig. 1). Air from a high-pressure compressor was supplied through a special diffuser (7) and distributed in the annular space between the inner and outer casings, bounded by the flame tubes (4). Air was supplied to the primary and secondary combustion zones in stages (through a system of holes in the flame tubes (3-6)); it was also used for film-cooling of the walls.

Gaseous fuel, consisting of an ammonia-hydrogen blend (2), along with the ecological steam (1), entered the combustor through the burner. The energetic steam was supplied separately via a dedicated pipeline (9). This steam was subsequently introduced to the flame tube through a system of holes, where it intensively mixed with the combustion products formed in the primary zone. After the additional supply of secondary air, the mixture of combustion products and steam (8) was directed to the turbine section of the gas turbine engine.

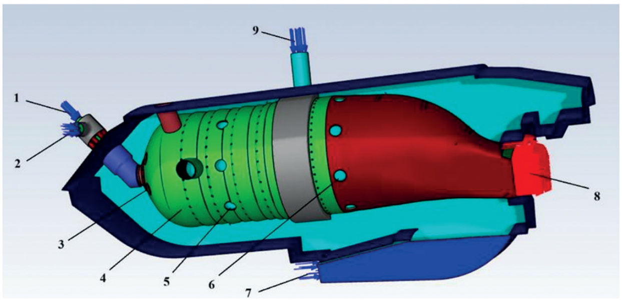


Fig. 1. Schematic of the steam-injected combustor: 1 – ecological steam supply; 2 – fuel supply (ammonia-hydrogen blend); 3 – front device with a vane swirler; 4 – flame tube (liner); 5 – primary air supply; 6 – secondary air supply; 7 – air supply from the high-pressure compressor via the combustor diffuser; 8 – combustion products outlet; 9 – energetic steam supply

Within the framework of developing low-carbon energy systems, it was proposed that the traditional use of natural gas in stationary systems be abandoned and the supply of an alternative fuel (an ammonia-hydrogen blend) be implemented through the burner assembly. The addition of hydrogen was aimed at increasing the chemical reactivity of the fuel and improving the stability of the combustion process.

It should be noted that the combustion process in the combustor was realised via a diffusion mechanism, i.e. without pre-mixing of the fuel-air mixture. This approach ensured the reliable and stable combustion of various fuel types across a wide load range. However, diffusion combustion is traditionally accompanied by the increased formation of NO_x. This drawback was significantly compensated for by injecting ecological steam directly into the intense combustion zone inside the flame tube, which helped to reduce temperature peaks and, consequently, NO_x levels.

To investigate the combustion processes in a combustor operating on an ammonia-hydrogen fuel blend, a mathematical model of chemically reactive gas-dynamic flows was developed. The model was based on the fundamental conservation equations for mass, momentum, and energy, as well as on the transport equations for individual chemical species in a multi-component mixture [23–25].

The mass balance equation describes the continuity condition of the flow:

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

The motion and energy state of the medium are determined by the conservation equations for momentum and total energy:

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

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot \big(\vec{v}(\rho E + p)\big) = -\nabla \cdot \vec{J}_q + S_h. \tag{3}$$

For each chemical species in the mixture, additional mass transport equations are solved, accounting for diffusion processes and chemical transformation:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla(\rho \vec{v} Y_i) = -\nabla \cdot \vec{J}_i + R_i + S_i. \tag{4}$$

In the above equations: ρ – mass density of the gaseous medium; $\vec{v}$ – velocity vector; S_m – source term characterising mass gain or outflow; p – static pressure; $\rho \vec{g}$ – gravitational force; $\vec{F}$ – vector of external forces; τ_{st} – stress tensor; E – specific total energy; Y_i – mass concentration of component i; $\vec{J}_q$ – heat flux vector of the mixture; $\vec{J}_j$ – diffusion flux vector of the j-th component; S_h – source term for heat release due to chemical reaction; S_i – additional formation rate of the i-th component from a dispersed phase or external sources; and R_i – net production rate of the i-th component due to chemical reactions.

For the numerical simulation of combustion processes, for the ammonia-hydrogen blend in the gas turbine engine combustor, the Eddy Dissipation Concept (EDC) model was applied. This model is an extension of the classical eddy dissipation model and combines turbulence description with detailed chemical kinetics [25].

Within the EDC approach, it is assumed that chemical reactions occur in localised, fine-scale turbulent structures, interpreted as 'micro-reactors'. The characteristic linear size of such structures, and the characteristic reaction times within them, are defined by the relations:

$$\xi^{*} = C_{\xi}\left(\frac{\nu\varepsilon}{k}\right)^{3/4}; \qquad C_{\xi} = 2.1377;$$

$$\tau^{*} = C_{\tau}\left(\frac{\nu}{\varepsilon}\right)^{1/2}; \qquad C_{\tau} = 0.4082, \tag{5}$$

where * indicates a fine-scale turbulent structure, C_ξ and C_τ and are empirical constants. The value of the characteristic scale ξ^* depends on the kinematic viscosity of the medium ν, turbulent kinetic energy k, and its dissipation rate ε.

Within the proposed modelling approach, chemical transformations were simulated using constant-pressure reactors, the initial state of each being defined by the temperature of the local mixture and the mass fractions of the reacting components at the inlet.

The kinetics of the elementary reactions can be described by Arrhenius-type dependencies and the numerical integration of the stiff chemical kinetics system was performed using the ISAT (In-Situ Adaptive Tabulation) algorithm. Under these conditions, the instantaneous molar production/consumption rate of the i-th chemical component can be determined by the relation:

$$R_i = \frac{\rho(\xi^*)^2}{\tau^*[1-(\xi^*)^3]}\,(Y_i^* - Y_i), \tag{6}$$

where Y_i^* is the mass fraction of the i-th reagent in the reactor volume after the characteristic reaction time τ^* has elapsed.

The characteristic time for chemical transformations in the fine-scale reactor is defined by the expression:

$$\tau^* = C_\tau\left(\frac{\nu}{\varepsilon}\right)^{1/2}, \tag{1}$$

where $C_\tau = 0.4082$ is the empirical time constant.

During the numerical experiments, sets of rate constants for the elementary reactions of the ammonia oxidation mechanism were used, selected to ensure acceptable agreement between the simulation results and the available experimental data.

For the analysis of the kinetic characteristics of the ammonia-hydrogen blend combustion process in air, the mechanism from [26] was applied. Overall, the utilised kinetic model included 203 elementary reactions involving 31 chemical species: NH_3, O_2, H_2O, H_2, H, O, OH, H_2O_2, HO_2, NO, N_2O, NO_2, HNO, HNO_2, HONO, $HONO_2$, N_2H_2, H_2NN, NH_2OH, HNOH, N_2H_4, N, NO_3, NH, NNH, NH_2, H_2NO, N_2H_3, Ar, N_2, and He.

DISCUSSION OF RESULTS

To analyse the characteristics of the working process in a 32 MW gas turbine engine combustor with steam injection, operating on an ammonia-hydrogen blend, numerical studies were performed using the ANSYS Fluent computational suite [27]. The simulations enabled detailed reconstruction of the flow structure, temperature distributions, and concentrations of chemical components in characteristic zones of the fuel-burning device, as well as an assessment of the influence of steam injection on combustion stability and emission characteristics.

Preliminary calculation results indicate that, when pure ammonia is supplied through the burner device, after local fuel ignition in the front device region, the flame does not propagate through the combustor volume; its stabilisation is not ensured, even under conditions of intense swirling of the primary air. This is due to the low reactivity of ammonia, limited flame propagation speed, and significant heat losses for heating inert mixture components.

In the regimes considered, the additional supply of ecological water steam through the front device leads to a further decrease in temperature in the combustion zone, which suppresses oxidation and chemical reactions and, consequently, causes flame extinction. The obtained results indicate the necessity of using activating additives, particularly hydrogen, as well as optimising the steam supply scheme, to maintain thermochemical conditions which are sufficient for the stable combustion of the ammonia-hydrogen blend.

The obtained preliminary numerical simulation results indicate that the use of pure ammonia as fuel in the investigated combustor with steam injection does not ensure the formation of a stable combustion flame across a wide range of operating regimes. This necessitates the modification of the fuel blend, to increase its reactivity and expand the stable combustion limits.

In this context, the introduction of hydrogen as an activating additive to ammonia is advisable. Hydrogen, characterised by low activation energy, high chemical reaction rates, and significant flame propagation speed, promotes the intensification of ignition processes and combustion stabilisation in the primary combustion zone. Furthermore, the presence of hydrogen increases the local temperatures and concentrations of active radicals (H, OH), which compensates for the cooling influence of water steam and ensures the maintenance of a continuous ammonia oxidation process within the combustor volume.

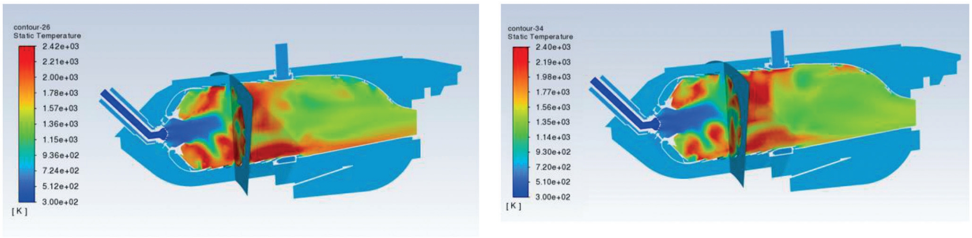
The results of the numerical simulation of the working process in the gas turbine engine combustor, when using a fuel blend containing 30% hydrogen by volume, are presented below. As preliminary studies showed, with a lower hydrogen fraction, flame stabilisation in the considered combustor is not achieved, even under conditions of intense flow swirling, which determined the choice of this specific fuel composition for further analysis.

Calculations were performed for one flame tube with the following initial parameters: air flow rate 2.318 kg/s, air temperature after the compressor 785 K; fuel blend flow rate through the burner 0.17 kg/s (with a volumetric content of 70% ammonia and 30% hydrogen); fuel temperature 300 K; total flow rate of ecological and energetic steam 0.6911 kg/s (at a superheated steam temperature of 743 K); and pressure in the combustor 2.634 MPa. Spatial discretisation of the computational domain was performed using a finite-difference grid, consisting of approximately 3.8 million tetrahedral cells, ensuring sufficient resolution for analysing thermochemical processes.

Two variants of flow rate ratio were considered for distributing ecological and energetic steam in the work: 1) 0.01/0.6811 kg/s (0.015); and 2) 0.1/0.5911 kg/s (0.170).

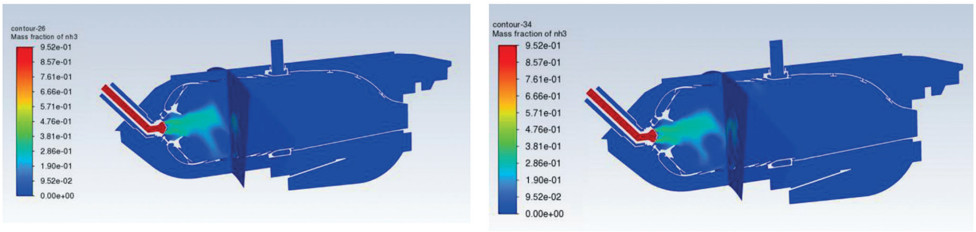
Fig. 2 shows the temperature fields for both variants in the characteristic cross-sections of the combustor.

Analysis of the obtained results shows that, for the first variant (0.015), a somewhat higher maximum temperature level is observed in the primary combustion zone near the front device. This is explained by the reduced amount of ecological steam being directly supplied to the flame formation region and, as a consequence, there is a reduction in the intensity of thermal dilution and cooling of the reaction zone. Increased



(a) **(b)**

Fig. 2. Temperature contours (K) in cross-sections of the combustor operating on an ammonia-hydrogen blend, at ecological to energetic steam flow rate ratios of (a) 0.015 and (b) 0.170



(a) **(b)**

Fig. 3. Contours of NH_3 mass fractions at ecological to energetic steam flow rate ratios of (a) 0.015 and (b) 0.170

local temperatures promote intensification of the initial stages of ammonia and hydrogen oxidation.

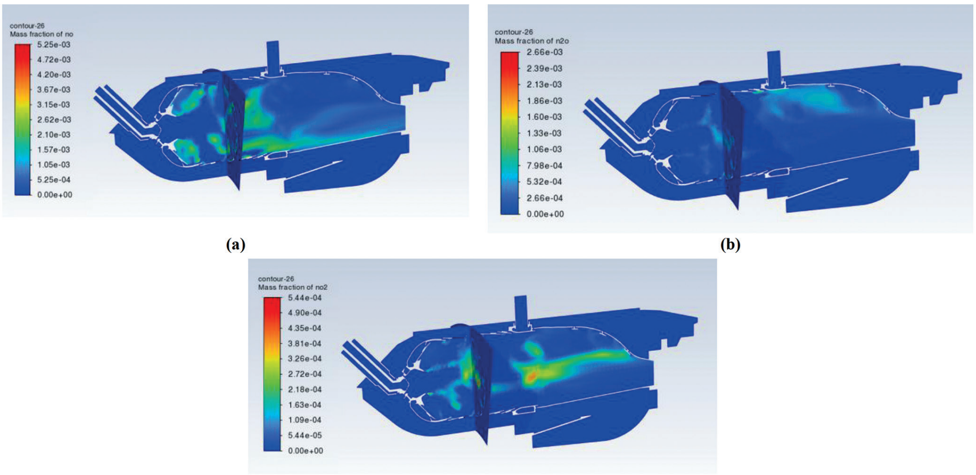
An important criterion for the efficiency of the working process is the completeness of ammonia burnout within the combustor volume. Even with hydrogen as a chemically active additive, intensive steam injection can lead to a decreased temperature and concentration of active radicals, negatively affecting the rate of NH_3 decomposition and oxidation reactions. Fig. 3 shows the distributions of ammonia mass fractions for both steam distribution variants.

Comparative analysis shows that, in the case of the second variant (0.170), ammonia burnout occurs at a significantly slower speed. This is confirmed by the volumetric NH_3 concentration values at the combustor outlet (582 ppm); whereas, for the first variant, this indicator decreases to 198 ppm. The obtained results indicate that an excessive supply of ecological steam to the main combustion zone substantially reduces the efficiency of ammonia oxidation, despite the presence of hydrogen.

To improve the completeness of ammonia burnout under such conditions, it is advisable to consider a set of different measures, including: increasing the swirl intensity of the air flow in the vane swirler, optimising the air distribution between the primary and secondary zones of the flame tube (to increase temperature in the frontal region), and applying methods of chemical combustion activation, particularly plasma technologies [28]. The plasma-based method utilises various plasma discharges [29,30], intensifies the processes of preparing ammonia for combustion, and increases the oxidation rate of ammonia, due to the high chemical activity of intermediate atoms and radicals [31].

Fig. 4 shows the contours of the main nitrogen oxides formed during the co-combustion of an ammonia-hydrogen blend in the GT combustor with steam injection at an ecological to energetic steam flow rate ratio of 0.015.

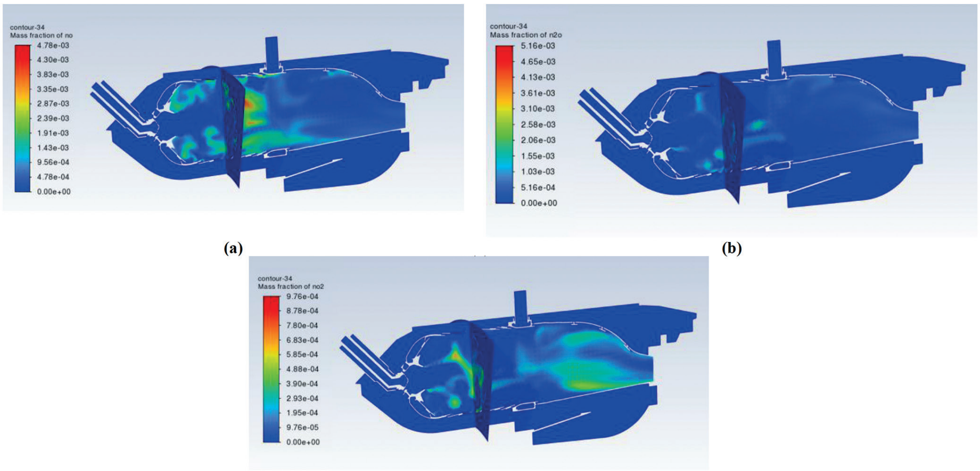
The results indicate that the dominant component in the NO_x composition is nitrogen oxide (NO), which is traditionally associated with its thermal formation mechanism. At the same



(a) **(b)**

(c)

Fig. 4. Contours of mass fractions of (a) NO, (b) N_2O, and(c) NO_2 at an ecological to energetic steam flow rate ratio of 0.015



(a) **(b)**

(c)

Fig. 5. Contours of mass fractions of (a) NO,(b) N_2O, and (c) NO_2 at an ecological to energetic steam flow rate ratio of 0.170

time, under the considered conditions, N_2O also constitutes a significant portion of total emissions, indicating the active participation of “fuel” mechanisms, which are characteristic of nitrogen-containing fuels. NO_2 predominantly forms in the peripheral and outlet zones of the flame tube under conditions of reduced temperatures and excess oxygen. The volumetric concentrations of NO, N_2O, and NO_2 at the combustor outlet are 472, 180, and 17 ppm, respectively.

Fig. 5 shows the contours of the main nitrogen oxides formed during the co-combustion of an ammonia-hydrogen blend in the GT combustor with steam injection at an ecological to energetic steam flow rate ratio of 0.170.

For the second variant, increasing the supply of ecological steam does not lead to the expected reduction in nitrogen oxide concentrations. On the contrary, an increase in N_2O and NO_2 content is observed, while the NO concentration remains at a similar level. The total concentrations of NO, N_2O, and NO_2 at the combustor outlet are 450, 263, and 39 ppm, respectively. This indicates that, under intensive steam dilution, the role of the classical thermal Zeldovich mechanism decreases, and the determining influence on NO_x formation begins to be exerted by complex pathways of nitrogen transformation from the ammonia composition through intermediate unstable radicals (NH_2, NH, and HNO).

CONCLUSIONS

We conducted a numerical investigation of the working process of a gas turbine engine combustor with water steam injection, operating on an ammonia-hydrogen blend. The main conclusions are summarised below.

1. For analysing combustion processes in a 32 MW GT combustor, a three-dimensional mathematical model of chemically reacting turbulent flows was applied, based on solving conservation equations for mass, momentum, energy, and the transport of chemical species.
2. Modelling was performed using a detailed kinetic scheme for the oxidation of an ammonia-hydrogen blend, including 203 elementary reactions involving 31 chemical components, and ensuring the correct description of both the thermal and fuel mechanisms of nitrogen oxide formation.
3. The stable operation of the combustor under steam injection conditions was only achieved with the introduction of no less than 30% hydrogen into the fuel blend, which is related to the intensification of chemical reactions and increased concentration of active radicals in the combustion zone.
4. It is established that, increasing the proportion of ecological steam in the primary combustion zone leads to a decrease in the temperature level and significant deterioration in the completeness of ammonia burnout, manifested in an increase of its concentration at the combustor outlet.
5. It is shown that, under conditions of intensive steam dilution, the formation of NO_x emissions is not only determined by the thermal mechanism but, also, by complex pathways of nitrogen transformation, from ammonia through intermediate radical compounds, causing an increase in the proportion of N_2O and NO_2 in the total emissions.
6. The obtained results indicate the necessity for further optimisation studies of the combustor design, particularly the distribution of air and steam, flow swirl parameters, and methods of chemical combustion activation, as well as experimental verification of the numerical results, to reduce nitrogen oxide emissions and improve the stability of the working process.

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