NUMERICAL ANALYSIS OF MICROMIXING IN CONCEPTUAL COMBUSTOR

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ABSTRACT

When a jet is introduced into a crossflow, a key fluid dynamic phenomenon known as micromixing improves fluid mixing. To encourage mixing of hydrogen with air prior to burning in a diffusion flame, hydrogen is delivered perpendicularly into an airstream in this study. The purpose of the combustor design is to shed light on the behavior of micromixing and how it affects combustion properties. The micromixing process is examined and its impact on flow dynamics is assessed using ANSYS Fluent. To maximize micromixing efficiency in both cold flow and combustion scenarios, the combustor geometry was specially designed. According to simulation data, there is better mixing in the center of combustor, which raises the temperature during combustion. Analysis of velocity and turbulence also shows how vortex generation and jet penetration contribute to improved micromixing. Better fuel-air mixing enhances combustion performance and stability, according to the study. Advanced cooling techniques will be investigated in future studies to control temperature distribution and avoid thermal hotspots. Additionally, optimization of injection parameters and combustor modifications will be considered to further enhance micromixing and overall combustion efficiency.

Keywords: micromixing, combustor, diffusion combustion, gas turbine, cfd, fuel mixing.

INTRODUCTION

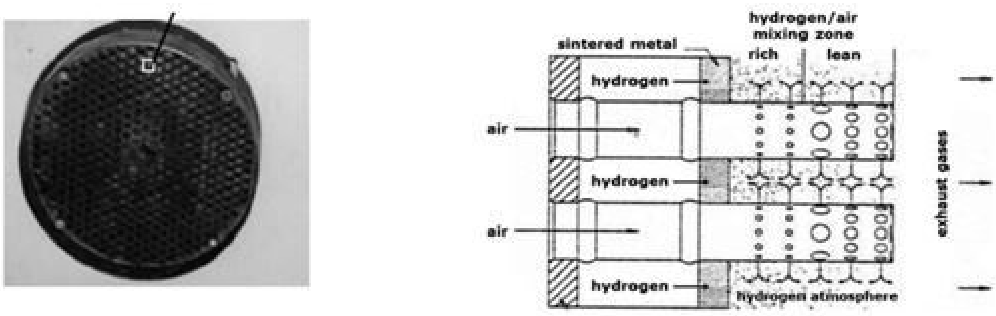
The term “conceptual” in this context refers to the design developed to incorporate the micromixing concept within the combustor. Combustion, a well-established process involving chemical reactions between air and fuel, generates flue gases that drive the turbine, while the high pressure produced by the compressor contributes significantly to the overall efficiency of the system. Despite the extensive understanding of combustion, ongoing research continues to focus on reducing pollutant emissions [1, 2] or facilitating the integration of alternative fuels such as biogas, green hydrogen, or a combination of both [3, 4]. This is particularly pertinent given that energy-related carbon dioxide (CO_2) emissions account for approximately two-thirds of global greenhouse gas (GHG) emissions [5].

Although hydrogen fuel is carbon-free, the high combustion temperatures promote thermal NOx formation, a mechanism in which atmospheric nitrogen (N_2) and oxygen (O_2) react to form nitrogen oxides (NOx) [6]. According to Lefebvre, the three key factors influencing NOx emissions are residence time, mixture composition, and reaction rate [7]. In gas turbine combustion, the temperature and pressure govern the reaction rate, and optimizing these parameters can impact turbine efficiency, even though it can aid in controlling NOx formation. For diffusion flames, optimizing the mixture is crucial in minimizing NOx production, as premixing increases the risk of flashback

[8]. The primary determinant of NOx formation is the residence time of reactants in the hot flame zone; longer residence times lead to higher NOx emissions. Thus, accurately predicting NOx emissions requires an integrated focus on temperature and flow dynamics [9].

Micromixing is a fluid dynamic phenomenon that occurs when jets interact with a crossflow, enhancing the mixing process [10]. In this method, hydrogen is injected perpendicularly into an airstream, allowing it to diffuse and be combusted. By utilizing rapid reaction rate of hydrogen, the residence time is reduced, and the reaction zone is divided into multiple diffusion flamelets rather than forming larger, singular flames.

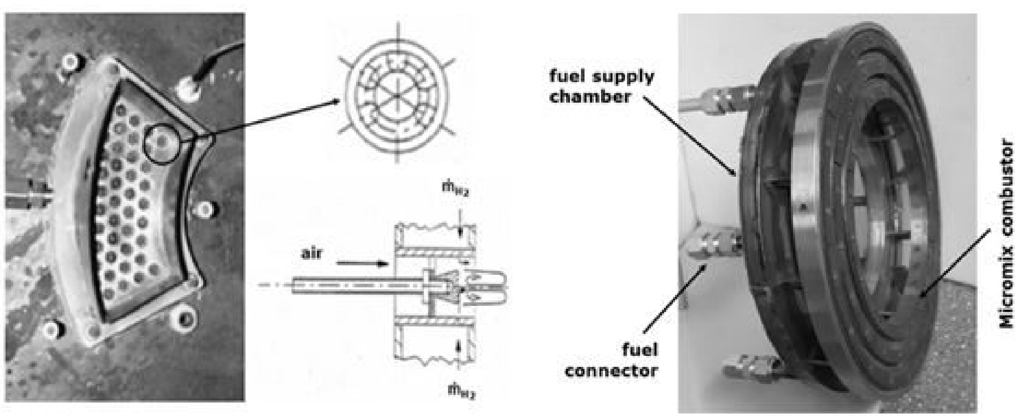
The sixth generation of micromixing technology is currently being utilized [11]. In the first generation (Fig. 1), multiple small air-injection tubes were incorporated into a single nozzle to facilitate perpendicular hydrogen injection. During testing, hotspots were observed at certain hydrogen injection points, and the design was found to be complex to construct and manufacture [11]. In the second generation (Fig. 1) of micromixing, a hydrogen-rich environment for air injection was created by introducing hydrogen into a sintered metal structure using inverse diffusion. However, the mechanical limitations of the sintered metal prevented continuous operation of this combustor. In the third generation (Fig. 2) of micromixing, six air-gate and hydrogen-injector systems were integrated into a single tube. These tubes were assembled to form a burner segment, and multiple segments were combined to create a combustor module. Nevertheless, excessive heat accumulation was observed at the front surfaces of the burner heat shields, resulting in thermal stress [12]. In the fourth generation (Fig. 2) of micromixing, 1600 hydrogen injectors were installed on six concentric rings that were uniformly spaced throughout the cross section of the combustion



1st Generation

2nd Generation

Fig. 1. Micromixing 1st and 2nd generation.



3rd Generation

4th Generation

Fig. 2. Micromixing 3rd and 4th generation.

chamber. Air moved along the axial direction of the flame tube into the ring combustor. Thermal stress on the ring segments and mild thermoacoustic impacts were noted during testing. Additionally, the manufacturing and assembly processes remained complex and costly. To improve power density, the fifth generation of micromixing (Fig. 3) was designed and improved for both can and annular combustors [11]. This generation made it possible to integrate the combustor in both forms with greater flexibility by employing a half-burner ring design inside a ring assembly. The objective of increasing power density [13] while preserving dual-fuel capacity with hydrogen-rich syngas propelled the creation of the sixth generation (Fig. 3) combustor [11].

In this study, the micromixing concept was applied to the existing geometry of the combustion chamber, and the mixing of reactants was analysed under cold flow conditions. Additionally, the reactant mixture was analysed through volumetric reaction analysis to gain insights into the flame structure, reaction zone, and temperature gradients.

EXPERIMENTAL

Methodology

A three-dimensional geometric model of the combustion chamber was created using SolidWorks, a CAD-CAE software (Fig. 4). The analysis was conducted using the finite volume method within the ANSYS Fluent environment. The analysis process involved five steps: designing the geometry, preprocessing (including discretizing the geometry through meshing and creating a grid for the model), inputting the necessary data for the simulation, performing the computations, and postprocessing (which included interpreting and presenting the results).

Combustor geometry

The 3D model with dimensions is illustrated in Fig. 4. The key dimensions are provided below. Hydrogen is introduced through the central feeder to the micromixing holes, each with a diameter of 0.6 mm, located on its circumference. Air is introduced perpendicularly to the

5th Generation 6th Generation

Fig. 3. Micromixing 5th and 6th generation.

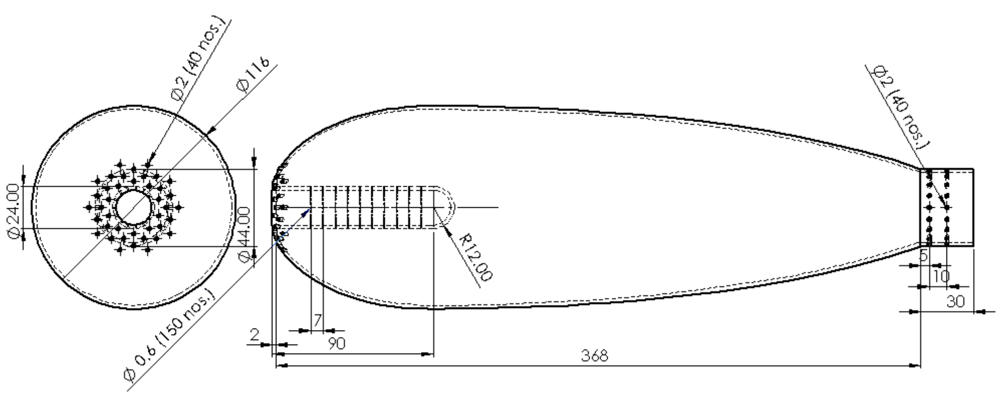


Fig. 4. The 3D model view with dimension.

hydrogen flow through surrounding holes, each with a diameter of 2 mm, facilitating thorough mixing.

Mesh generation

ANSYS Meshing, a discretization software, was used for grid generation. After analysing successive grid refinements, it was observed that, for a grid above 460662 nodes and 2614729 elements (Fig. 5), the change in the temperature profile became negligible, with a variation typically within 1.5 % [14]. Therefore, the solution was considered grid independent. The mesh quality, measured by skewness and orthogonality, was maintained at optimal levels according to established standards. The 3D computational mesh was created with a skewness of less than 0.92, an aspect ratio of less than 13.2, and a minimum orthogonal quality of 0.07, in compliance with the mesh quality appendix A -guideline provided by Ansys Inc.

Governing equations

For Numerical simulation, mass, momentum, and energy conservation equations along with species transport equations were used within the Fluent CFD code. The governing equations are presented below [15].

Continuity:

$$\frac{\partial \rho U}{\partial t} + \nabla . \rho U = 0 \quad (1)$$

Momentum

$$\frac{\partial \rho U}{\partial t} + (\nabla . \rho UU) = - \nabla p + \nabla \cdot \tau + \rho g \quad (2)$$

Energy

$$\frac{\partial \rho h}{\partial t} + \nabla . \rho U = \nabla . \lambda e \nabla T - \nabla . q_r + $$
$$+ \nabla . \Sigma_l \rho h_l (T) D_e \nabla m_l \quad (3)$$

Temperature

$$\rho C_p \frac{DT}{Dt} = \nabla \cdot \lambda e \nabla T - \nabla . \Sigma_l \rho h_l (T) D_e \nabla m_l - $$
$$- \rho \Sigma_l \frac{Dm_l}{Dt} h_l (T) \quad (4)$$

Species mass fraction

$$\frac{\partial \rho m_l}{\partial t} + \nabla \cdot \rho U m_l = \nabla . De\rho \nabla m_l - R_l \quad (5)$$

Moreover, it can be seen in literature that RNG k-ε turbulence model and eddy-dissipation model of combustion result in satisfactory values for such works [16]. The Reynolds-Averaged Navier-Stokes- RANS solution used realizable k-ε turbulence model [17].

The chemical kinetics use the following global reaction.

$H_2 + 0.5\ O_2 \rightarrow H_2O$

Boundary conditions

The inlet boundary conditions for air and hydrogen were specified as constant mass flow inlets, while an exhaust pressure outlet was selected as the outlet condition. The inlet condition for hydrogen was defined as a mass flow inlet of 0.004 kg s^{-1}. The air inlet

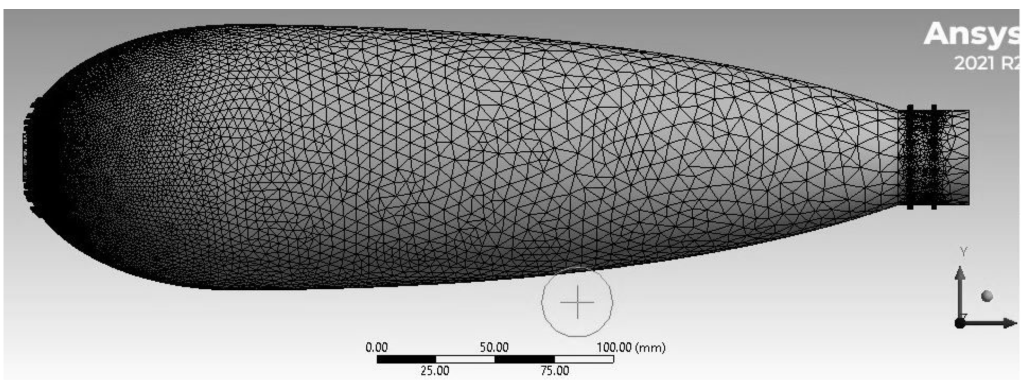


Fig. 5. Meshing model.

conditions were set with a mass flow rate of 0.3 kg s^{-1} from the main hole and 0.2 kg s^{-1} from the dilution hole. Both fuel and air were assumed to be at atmospheric pressure and temperature. The simulation was conducted in ANSYS Fluent, considering steady-state flow.

RESULTS AND DISCUSION

To investigate the mixing behaviour of hydrogen with air, a cold flow analysis was conducted, while the combustion characteristics were assessed through reaction simulations. The corresponding simulation results are presented below.

Cold flow analysis results

A cold flow analysis was performed to analyse the mixing behaviour of the micromixing design. The research aimed at knowing the distribution of mixture fractions of fuel and oxidizer (hydrogen and air) along the longitudinal plane, as shown in the Fig. 6 and Fig. 7. The findings show that the mixing process is affected considerably by the pressure gradients created within the chamber. Hydrogen is directed towards the chamber exit on entering the combustion chamber due to the inlet velocity and air pressure perturbations. Continuous mixing along the chamber length was ensured by the uniform diffusion of hydrogen into the airstream. However, localized variations in the mixture fraction were identified, indicating regions where mixing was less uniform, potentially requiring further optimization of the micromixing design.

Result with chemical reaction

The volumetric reaction option of the species transport model was activated to simulate the chemical reaction of combustion, enabling the interaction between the oxidizer and fuel to be replicated throughout the combustion process. By integrating reaction kinetics with the transport equations for chemical species, combustion reactions were predicted with greater accuracy.

The temperature contour plot, shown in Fig. 8, illustrates the temperature distribution along a longitudinal plane through the centerline of the combustion chamber. A

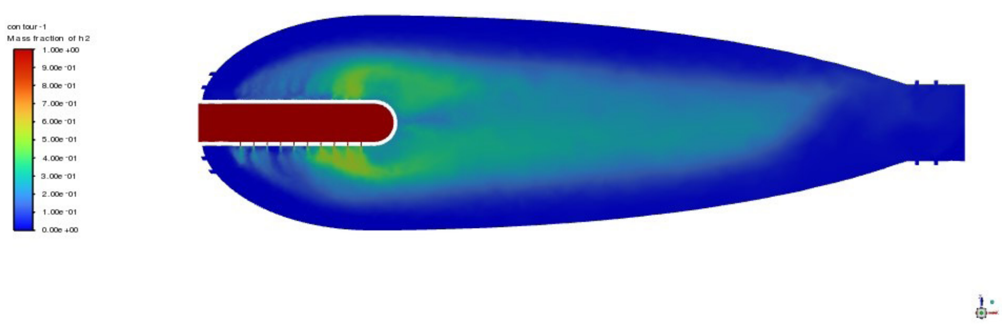


Fig. 6. Mixture fraction of hydrogen.

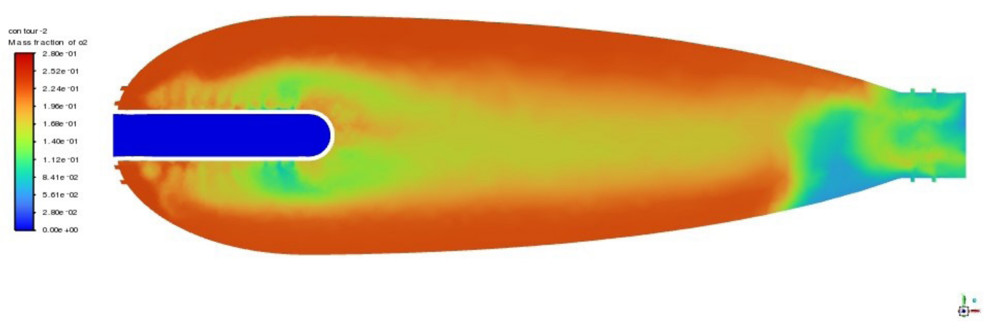


Fig. 7. Mixture fraction of oxygen.

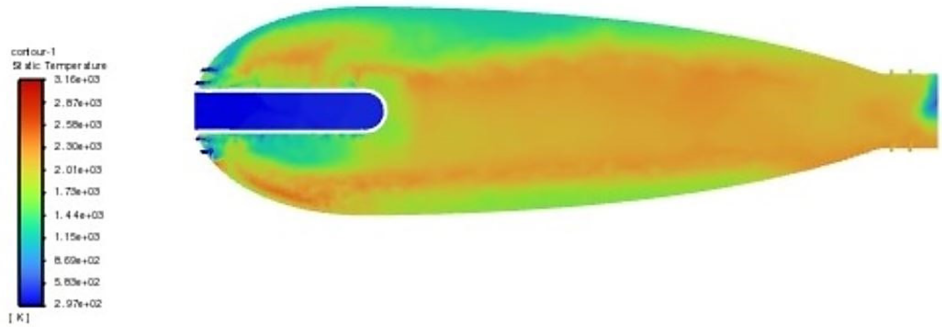


Fig. 8. Static тemperature.

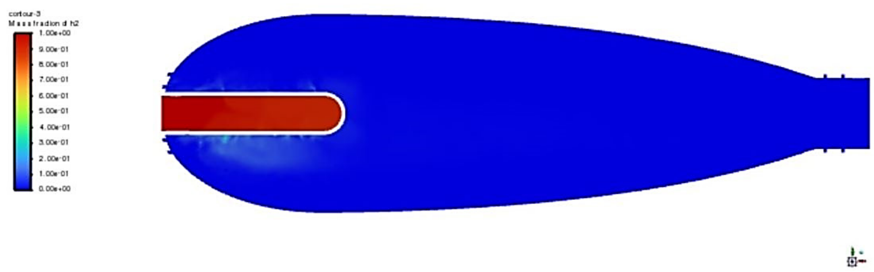


Fig. 9. Mass fraction of hydrogen after combustion.

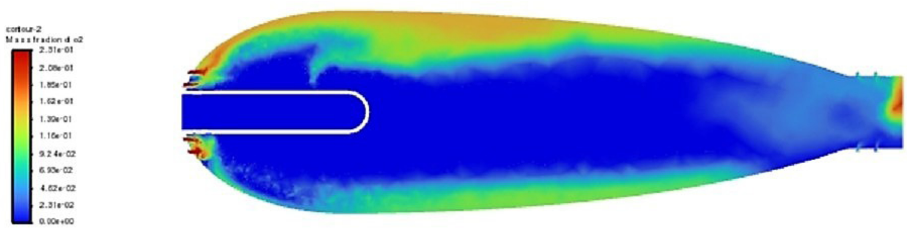


Fig. 10. Mass fraction of oxygen after combustion.

substantial temperature increase was observed due to the exothermic nature of the hydrogen combustion process. As hydrogen reacted with the oxidizer, energy was released, resulting in a noticeable rise in static temperature throughout the combustion zone. The temperature peaked in regions where optimal mixing ratios of reactants were achieved, ensuring efficient combustion. The maximum temperature was recorded in the range of 2300-2350 K [18].

As shown in Fig. 9, when hydrogen combustion is complete, the exhaust stream exhibits an almost negligible mass fraction of hydrogen. This observation indicates the high efficiency of the combustion process, as all available hydrogen is consumed in the reaction. The reduction in hydrogen concentration along the axial direction of the chamber further demonstrates efficient fuel consumption, contributing to achieve the required thermal efficiency and minimizing unburned fuel emissions

The inclusion of excess air is a commonly employed for hydrogen-fuelled systems, where minimizing fuel loss is critical for achieving high thermal efficiency and preventing safety risks associated with residual hydrogen. Also, excess air contributes to temperature regulation within the combustion chamber. By introducing additional mass into the system, the heat generated by the exothermic combustion reaction is distributed more evenly, leading to a reduction in peak temperatures [19]. This mitigates the risks of thermal stresses on the chamber walls and helps to control the formation of nitrogen oxides (NO_x), which are temperature-dependent pollutants. Fig. 10 illustrates the spatial distribution of oxygen mass fraction within the chamber in combustion. The results indicate that the oxygen content is entirely consumed along the axial length of the combustion chamber, corresponding to regions of active combustion where oxygen reacts with hydrogen. However, the presence of excess oxygen is observed near the wall areas, as shown in the figures.

CONCLUSIONS

The conceptual combustor, designed for micromixing, was analysed for both cold flow mixing and combustion reactions. The mass fraction plot indicates that distinct mixing occurs near the central zone of the combustor. Additionally, combustion characteristics were simulated using FLUENT. The results obtained from the RANS simulation indicate elevated temperatures, ranging from 2300 to 2350 K, at the center of the combustor where combustion takes place. To manage these temperatures, a substantial amount of cooling air will be required. However, further experimental testing is necessary to validate the simulated results, particularly concerning the temperature and flow fields.

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***Authors' contributions**: J.P.: wrote this paper as a part of his PhD study at GTU; D.K. guided in the design of combustor and V.D.: Supervised research, guided simulations, and assisted in analysis.*

REFERENCES

1. A. Datta, S. Som, Combustion and emission characteristics in a gas turbine combustor at different pressure and swirl conditions, Appl. Therm. Eng., 19, 1999, 949-967.
2. N. Guellouh, Z. Szamosi, Z. Siménfalvi, Combustors with low emission levels for aero gas turbine engines. Int. J. Eng. Manage. Sci., 4, 1, 2019, 503-514.
3. K. Gupta, A. Rehman, R. Sarviya, Bio-fuels for the gas turbine: a review, Renew. Sustain. Energy Rev., 14, 9, 2946-2955.
4. S. Serbin, M. Radchenko, A. Pavlenko, K. Burunsuz, A Radchenko, D. Chen, Improving ecological efficiency of gas turbine power system by combusting hydrogen and hydrogen-natural gas mixtures, Energies, 16, 2023, 3618.
5. S. Rai, M. Massey, D. Massey, A review on green hydrogen: an alternative of climate change mitigation, Indian J. Adv. Chem. Sci, 9, 4, 2021, 340-345.
6. J. Santner, A. Sheikh, T Farouk, F. Dryer, Computational study of NO_x formation at conditions relevant to gas turbine operation, Energy & Fuels, 1, 2016, 1-32.
7. A.H. Lefebvre, Fuel effects on gas turbine combustion-liner temperature, pattern factor, and pollutant emissions, J. Aircraft, 21, 11, 1984, 887-898.
8. J. Ziemann, F. Shum, M. Moore, D. Kluyskens, D. Thomaier, N. Zarzalis, H. Eberius, Low-NOx combustors for hydrogen fueled aero engine, Int. J. Hydrogen Energy, 23, 4, 1998, 281-288.
9. Z. Wang, X. Yang, NOx formation mechanism and emission prediction in turbulent combustion: a review, Appl. Sci., 14, 2024, 6104.
10. S. Boerner, H. H. W. Funke, P. Hendrick, E. Recker, R. Elsing, Development and integration of a scalable low NOx combustion chamber for a hydrogen-fueled aerogas turbine, Prog. Propuls. Phys., 4, 2013, 357-372.
11. H.H. W. Funke, N. Beckmann, J. Keinz, A. Horikawa, 30 Years of Dry-Low-NOx micromix combustor research for hydrogen-rich fuels: an overview of past and present activities, J. Eng. Gas Turbine Power, 143, 7, 2021, 1002-1015.
12. G. Dahl, F. Suttrop, Engine control and low-NO_x, combustion for hydrogen fuelled aircraft gas turbines, Int. J. Hydrogen Energy, 23, 8, 1998, 695-704.
13. H.H.W. Funke, N. Beckmann, J. Keinz, S. Abanteriba, Comparison of numerical combustion models for hydrogen and hydrogen-rich syngas applied for dry-low-Nox-micromix-Combustion, J. Eng. Gas Turbines Power, 140, 8, 2018, 1504-1513.
14. R.G. Bhuvana, S. Srinivasan, T. Murugan, CFD analysis on swirl angle effect in gas turbine combustion chamber, IOP Conf. Ser.: Mater. Sci. Eng., 402, 2018, 012206.
15. J. Fernández, J. Ruiz, J. Lacuna, Study of combustion using a computational fluid dynamics software (ANSYS), University of Barcelona, 2016, 15-18.

16. N. Kahraman, S. Tangöz, S. Akansu, Numerical analysis of a gas turbine combustor fueled by hydrogen in comparison with jet-A fuel, Fuel, 217, 2018, 66-77.
17. H. Nagarajan, M. Rangasamy, M. Kunchi, V. Boddu, Numerical analysis of fuel mixing physics in gas turbine combustor. Proceedings of the 21st Annual CFD Symposium, Bangalore, 2019, 57-62.
18. E. Shchepakina, I. Zubrilin, A. Kuznetsov, K. Tsapenkov, D. Antonov, P. Strizhak, D. Yakushkin, A. Ulitichev, V. Dolinskiy, M. Morales, Physical and chemical features of hydrogen combustion and their influence on the characteristics of gas turbine combustion chambers, Appl. Sci., 13, 2023, 3754.
19. M. Emami, S. Hamidreza, B. Sunden, Effect of operational parameters on combustion and emissions in an industrial gas turbine combustor. J. Energy Resour. Technol., 141, 1, 2018, 012202.