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Numerical and Experimental Analysis of Combustion Characteristics of Gas Turbine Engines

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Abstract
Advanced computational fluid dynamics (CFD) methods were used to carry out the numerical analysis. It was created a three-dimensional CFD model to represent the intricate flow and combustion processes inside the gas turbine engine. Fuel injection, combustion kinetics, and the effects of turbulence were all taken into account by the model. In order to analyse several combustion factors, such as temperature distribution, species concentrations, and flame propagation, numerical simulations were run.Experimentation was done in order to verify the numerical results and understand the combustion properties better. To simulate the operational circumstances of a gas turbine engine, a test setup was created. Measurements of combustion parameters, including pressure, temperature, and emissions, were made and compared to the numerical forecasts. The computational model might then be verified and improved as a result.The findings of this study offer insightful information about how gas turbine engines behave during combustion. The temperature distribution, species concentrations, and flame propagation within the engine were all correctly predicted by the numerical models. The experimental observations showed good agreement with the expected values, confirming the accuracy of the numerical model. This thorough examination aids in the comprehension of gas turbine engine combustion processes and can be used as a foundation for future design enhancements and performance enhancements.

Keywords: Gas turbine, DLE, micro gas turbine, bio-gas combustion, Emission

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Introduction

In landfills and anaerobic digesters, where it is created as a byproduct in the absence of oxygen, biogas is largely produced through the breakdown of organic waste. In addition to utilising materials that would otherwise be useless and limiting the production of methane, a harmful greenhouse gas that contributes to global warming, this procedure offers an appealing and possibly renewable energy source [1]. Methane has a global warming effect that is around 21 times greater than carbon dioxide because of its ability to trap heat radiated from the Earth [2]. In order to reduce the environmental impact of the methane created during the decomposition of organic waste, it must be handled by burning as opposed to being released into the atmosphere.Additionally, as biomass is regarded as a renewable energy source, using biogas has the added advantage of lowering dependency on fossil fuels. Methane (CH4), carbon dioxide (CO2), and nitrogen (N2) make up the majority of the composition of biogas from landfills, though the quantities of these elements may change depending on the gasification process utilised and the particular feedstock used [3].

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Utilising biogas allows us to manage waste more effectively while simultaneously generating sustainable energy and lowering greenhouse gas emissions.
The use of biogas in gas turbines has been extensively studied, making use of the fact that biogas may efficiently produce power from waste products. Biogas-specific specialised combustors have been used to optimise its use, leading to favourable combustion and operational performance in gas turbines [4-6]. Experimental studies have been done to examine the viability and effectiveness of using biogas in various contexts.
Due to its many benefits, such as its small size, high efficiency, and capacity to use various fuel types, the micro-gas turbine has received a lot of attention recently [20,21]. This technology has found use in hybrid electric car power sources as well as distributed power generating.The variety of fuel alternatives available to micro-gas turbines is one of their significant advantages. The gas turbine engine may function efficiently with a variety of fuel types, including natural gas, syngas, biogas, and diesel, depending on the particular application [22]. This versatility in fuel choice enables adaption to various energy sources and needs.In situations where compact size and high efficiency are important considerations, micro-gas turbines present an alluring option for decentralised power generation. They are suitable for small-scale power generation systems due to their compact design, which makes installation simple in locations with limited space. Their great efficiency also helps to enhance energy efficiency and lessen environmental impact. Micro-gas turbines have moreover become practical power sources for hybrid electric vehicles. They are suited for delivering on-board power generation in electric vehicles, extending their range and lowering reliance on conventional fossil fuels, thanks to their small design and multi-fuel capacity.
The investigation of a combustor created specifically for the micro-gas turbine using biogas as fuel is still ongoing. The effect of fuel composition, fuel injector position, and fuel pilot split on combustion performance was looked at in a previous experimental investigation [9]. The results showed that fuel jet velocity and fuel pilot split have a substantial impact on combustion efficiency. To fully comprehend the impacts of air flow characteristics and fuel jet characteristics on fuel/air mixing, as well as the consequent impact on combustion characteristics in the combustors, more research is nonetheless required.By going into further detail into the fuel/fuel mixing performance and its effects on combustion performance for a particular biogas fuel, this present work seeks to build on the prior study. In order to better understand how air flow, fuel jet, and fuel/air mixing interact to effect the whole combustion process within combustors, researchers are focused on mixing performance. An improved knowledge of the intricate interactions between fuel characteristics, flow dynamics, and combustion processes in micro-gas turbine combustors running on biogas will be possible thanks to this in-depth investigation, which will offer vital insights into the optimisation of combustion performance.

I. Conditions for the Combustor

A two-stage axial swirler is incorporated into the combustor. To assist a reverse flow feature along the combustor's axis and cause a vortex breakdown, the swirler for the pilot burner is constructed with a larger swirl number. The internal reverse flow zone (also known as the centre recirculation zone, or CRZ) is the name given to this particular flow characteristic. The combustion process is optimised by adding the CRZ, promoting steady and effective combustion inside the combustor.A pilot fuel schedule can be used to successfully regulate the lean combustion instabilities, such as

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lower flame-holding and larger combustion dynamic pressure amplitude [6]. To maintain combustion stability in the design, centrally staged combustion technology is used.Figure 1 shows the structure and section diagram of the counter flow combustor that was specifically created for the micro-gas turbines. Lean premixed combustion technique is used in the combustor to reduce pollutant emissions.

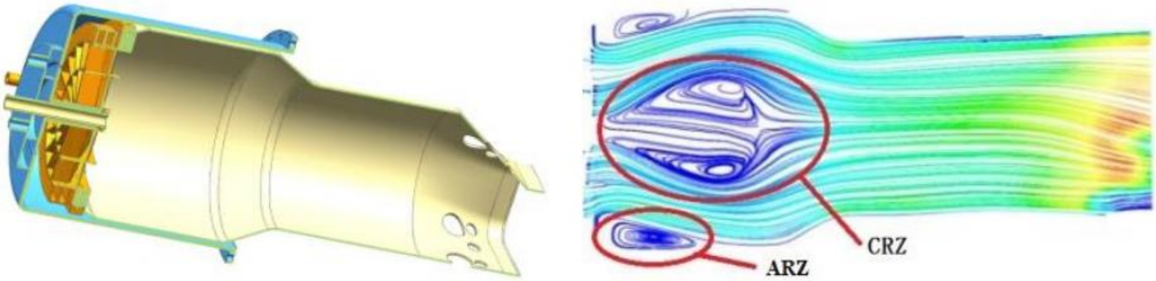

Figure 1: Flow feature combustor representation

In order to improve combustion performance, reduce pollutant emissions, and increase combustion stability in the micro-gas turbine combustor, a counter flow configuration, lean premixed combustion technology, and centrally staged combustion are implemented. These design factors help the combustor operate effectively and dependably, making it appropriate for using biogas as a fuel source in micro-gas turbines.

The fuel intake, which is made up of fuel inlets 1 and 2, is where the fuel is introduced into the combustor. Together with swirler 1, these fuel inlets provide a pilot burner that is essential for maintaining combustion stability in the combustor. This particular layout of the pilot burner is intended to support dependable and reliable combustion.To reduce pollutant emissions, a premixed combustion technique is used for the combustor's main combustion stage. The main combustion stage fuel nozzles are located at various points inside the combustor, as shown in Figure 2, and they are designated as fuel inlets 3 and 4. This configuration aims to investigate and assess the impact of the main stage nozzle position.

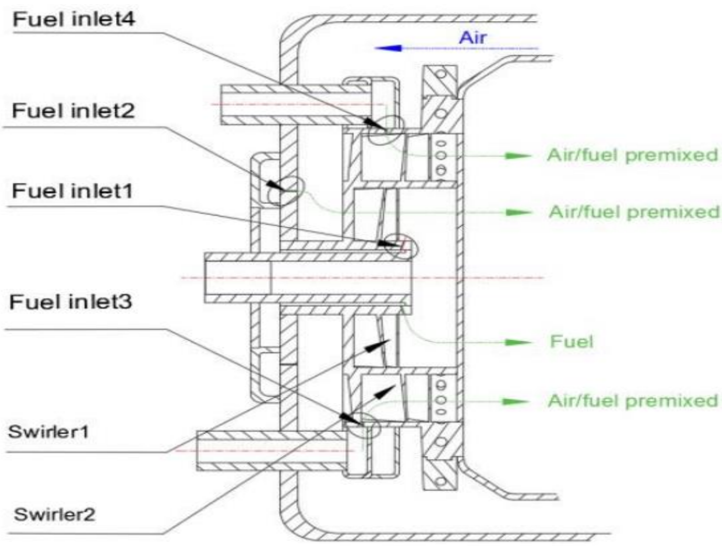

Figure 2: Combustor head with two swirlers and four fuel inlets

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The regularity of fuel and air mixing is crucial in determining NO_x emissions in a lean premixed combustion system. The parameters of the air flow and the effectiveness of the fuel injection both have an impact on the amount of mixing homogeneity. This research focuses on comprehending the impacts of air flow characteristics and fuel injection characteristics on fuel/air mixing and combustion within the combustor in order to thoroughly analyse this relationship.The air and fuel conditions at the combustor inlet will be held constant throughout the investigation. The researchers are able to examine the precise effects of these aspects without using confounding variables by separating the effects of air flow and fuel injection characteristics on the fuel/air mixture and combustion characteristics.

This method makes it possible to assess mixing and combustion performance in the combustor in a systematic manner, giving significant information for lean premixed combustion system optimisation. The research will help develop methods for improving fuel/air mixing homogeneity, which will increase combustion efficiency and decrease NO_x emissions in gas turbine applications.The swirler introduces the air into the combustor, where it mixes with the fuel before the chemical reaction occurs. The swirler's layout and design have a significant impact on the air flow characteristics inside the combustor. The swirler's structural properties are determined by variables like the number of blades (n) and the angle of the blades (S_n).

The swirl number (Sn) is used as a characteristic parameter to measure the swirling motion produced by the swirler. The following equation defines the swirl number, which is determined by the structural characteristic parameters of the swirler:

$$Sn = \left(\frac{4\pi(R2^3 - R1^3)(\sin\theta)}{3nc(R2^2 - R1^2) * (R2 - R1)}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where, The variables in this equation stand for the following:
R1: The swirler's inner boundary's radius
R2: The swirler's outer boundary's radius
θ: Angle of the swirler blade
n: The swirler's number of blades
c: Swirler's axial chord length

Table 2: The combustion chamber architecture

Case	**θ**	**n**	**Sn**	**d**	**np**	**α**
1	38	23	0.762	1.6	M	92
2	46	21	0.826	1.6	M	92
3	65	21	1.137	1.6	M	92
4	65	17	0.847	1.6	M	92
5	65	29	1.364	1.6	M	92
6	65	21	1.137	1.2	M	92
7	65	21	1.137	2.1	M	92
8	65	21	1.137	1.6	F	92
9	65	21	1.137	1.6	M+F	92

The case numbers for each case are listed in this table along with values θ for the swirler blade angle, number of blades, swirl number, diameter, main stage nozzle position, and angle.The fuel-air mixing process is significantly impacted by the diameter of the fuel nozzle, which also influences the depth and momentum of the fuel jet. As shown in Table 2, three distinct nozzle diameter values were used for this study: d = 1 mm, 1.5 mm, and 2 mm. For examples 3, 6, and 7, in particular, the nozzle diameter was the only variable that changed while all other factors remained the same. This experimental layout made it possible to examine how nozzle diameter adjustments affected mixing and combustion efficiency.

When using various fuel nozzle sizes, the fuel pressure was modified appropriately to maintain a constant fuel mass flow rate. This made sure that regardless of the various scenarios, the overall amount of fuel entering the combustor remained constant.Additionally, as shown in Figure 2, the location of the main combustion stage fuel nozzle within the combustor might be changed. The chance to investigate the impact of nozzle placement on fuel-air mixing and combustion performance was made possible by the flexibility in nozzle position.This research intends to improve understanding of these crucial factors and their effect on the overall performance of the combustor by methodically examining the impacts of nozzle diameter and position on the mixing and combustion characteristics. These perceptions aid in improving fuel-air mixing and combustion effectiveness in gas turbine applications.

II. Data System Design Experimentation

Delivering air to the combustor is the responsibility of the air supply system. It has an orifice flowmeter that allows for accurate air flow measurement with a 1.2% full scale (FS) error tolerance. The combustion inlet air temperature can also be adjusted within a range of 30 to 580 °C using a specially made control module.Figure 3 depicts the experimental test setup used to investigate combustion performance. The air supply system, fuel supply system, ignition system, and test system are only a few of the system's essential parts.The fuel supply system is made to give the combustor the fuel it needs. The experiment's gas fuel is created by combining CH_4, CO_2, and N_2 in a mixing apparatus.

Gas mass flow metres with an error tolerance of 1% FS are used to gauge the flow rate of each gas component.The fuel-air mixture in the combustor is successfully ignited by the ignition system. The abstract does not contain particular information about the equipment or exact igniting technique used.A Testo 350 flue gas analyzer is part of the test system, and it is used to measure the exhaust gas leaving the combustor. This analyzer offers useful details on the make-up and traits of the combustion products, assisting in the evaluation of combustion efficiency.The output power of an electric heater and an air conditioning valve can be changed in order to regulate and alter the inlet conditions of the combustor. This makes precise manipulation possible.

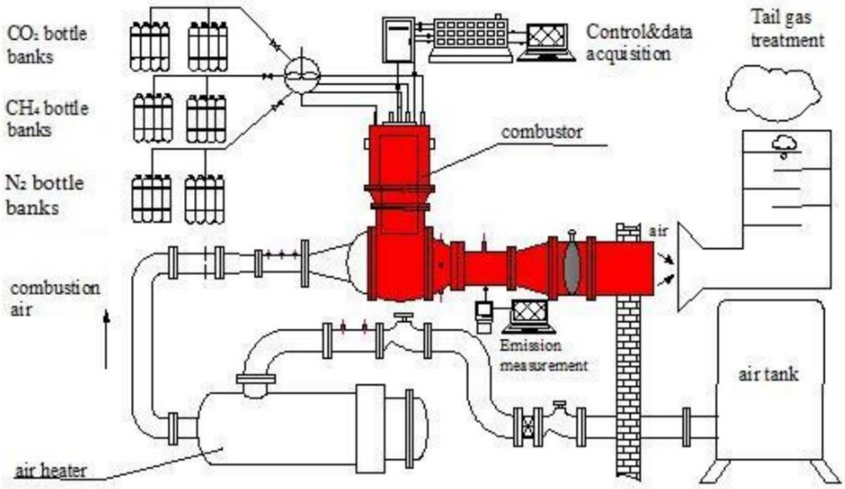

Figure 3: System Design Experimentation system

III. Computing Model and Governing Equations

The component transfer equation, together with the conservation equations for mass, momentum, and energy, are all combined in the mathematical model used in this study. A large eddy simulation (LES) model, which represents scalar variables inside a three-dimensional (3D) domain including a gas turbine combustor, is used to solve these equations. The mass and momentum conservation equations as well as the species transport equation are all included in the model. The LES model can be used to correctly capture and analyse the complex interactions and dynamics of the flow, species concentrations, and heat transport within the gas turbine combustor.

$$\frac{\partial(\rho Uj\varphi + \rho uj\phi)}{\partial xj} = \frac{\partial\left(\frac{\Gamma\phi\partial\varphi}{\partial xj}\right)}{\partial xj} + \rho s\varphi \qquad (1)$$

Where, The different spatial coordinate directions, such as x, y, or z, are represented by the subscripts j. The terms density, mean velocity component, fluctuation velocity component, diffusion coefficient, and source term are represented by the variables, U_j, u_j,, and _s, respectively. The scalar variable of interest is represented by the variable. The equation explains the contribution from the source term as well as the conservation of the convective and diffusive fluxes.The fundamental goal of LES is to ignore vortices that are less than a predetermined size while keeping those that have a major impact on the flow field. As a result, the computational resources can be concentrated on resolving the turbulent structures that have the greatest influence, producing simulations that are more effective.

$$\phi(x,t) = Z\, G(r,x)\phi(x - r,t)dr \qquad (2)$$

Using continuity and the Navier-Stokes equations, a general equation can be derived.

$$\partial\rho/\partial t + \partial(\rho ui)/\partial xi = 0 \qquad (3)$$

This equation illustrates the continuity equation, which asserts that the divergence of the mass flux (ui) and the rate of change of density with respect to time are both equal to zero. It illustrates how mass is conserved in a fluid system.

Stress is produced at a subgrid size as a result of filtering procedures in turbulence modelling. The modelling approach heavily relies on this subgrid scale stress. The filtered static pressure term is mixed with the isotropic component of the subgrid scale stress to take this into account. On the other side, turbulent viscosity is used to model the deviation portion of the subgrid scale stress.

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These terms improve the simulation's accuracy by helping the turbulence model reflect the impacts of the subgrid scale stress.

$$\mu t = \rho L^2 * [s(S\_dijS\_dji)^{(3/2)} * (S\_ijS\_ji)^{(5/2)} + (S\_dijS\_dji)^{(5/4)}] \quad (4)$$

Where, μt represents the turbulent viscosity,ρ is the density,L is a characteristic length scale,S_ij is the resolved strain rate tensor,S_dij is the deviatoric part of the resolved strain rate tensor.

The distinct mixture fraction and the density weighted average scalars were used to compute the probability density function and progress variable. The following equation was used to compute the species fraction.

$$\varphi = c \int_0^1 \varphi\_b(f)\, p(f)\, df + (1 - c) \int_0^1 \varphi\_u(f)\, p(f)\, df \quad (5)$$

where u and b stand for the combinations that haven't burned and have, respectively.

IV. Mixing characteristics of fuel and air

The mixing non-uniformity can be measured by computing the squared difference between the species fraction at each sampling point and the average species fraction, adding those results, and then normalising them. A lower value denotes a more even distribution of fuel and air.

The following definition can be used to calculate the mixing non-uniformity of fuel and air:

$$\text{Non} - \text{uniformity} = \sqrt{(\sum((C\_i - C\_avg)^2 / C\_avg^2) / N)} \quad (6)$$

In this equation:

- Non-uniformity represents the measure of mixing non-uniformity,
- C_i represents the species fraction of a specific component (fuel or air),
- C_avg represents the average species fraction of that component,
- N is the total number of sampling points.

The mixing non-uniformity can be measured by computing the squared difference between the species fraction at each sampling point and the average species fraction, adding those results, and then normalising them. A lower value denotes more evenly mixed fuel and air.

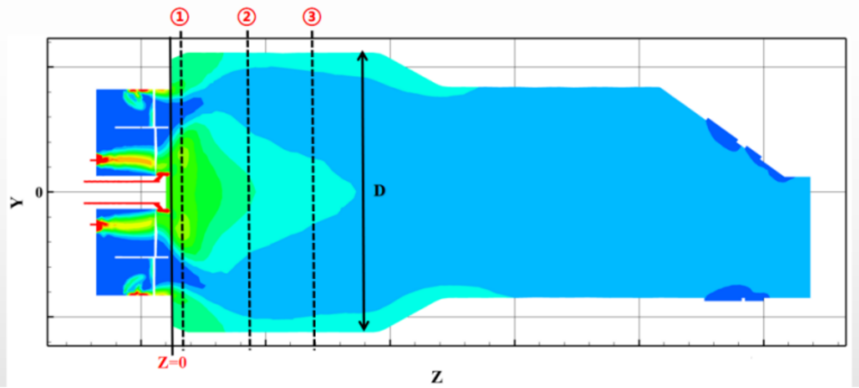

Figure 4: chosen monitoring plane placement in the combustion chamber. Flow speeds are represented using colours.

The similarities in fuel distribution between the three scenarios can be attributed to the compact design of the combustor head and the short premixing channel at the main combustion stage. As a result, the primary combustion stage's nozzle position modification has little effect on the mixing efficiency. This is so that a slightly longer channel may be created for premixing by placing fuel inlet 3 in front of fuel inlet 4. The position of the fuel nozzle has a little impact on mixing performance because of the small amount of space and short distance available for premixing.

V. Combustion Efficiency

Combustion efficiency and combustor exit temperature fluctuation were two metrics used in this study to assess how well the combustor performed during combustion. These variables shed light on the behaviour and general performance of the combustion process.An key indicator of how efficiently fuel is burned is combustion efficiency. It displays the proportion of fuel that is transformed into usable energy. More thorough burning and greater use of the fuel's energy content are implied by increased combustion efficiency.

Another metric worth paying attention to is the variability of the combustor outlet temperature since it illustrates how stable and reliable the combustion process is. The durability and overall performance of the gas turbine engine may be affected by temperature variations. Increased mechanical stress and potential problems with turbine blade cooling may result from greater temperature changes.Although the stability map, which investigates the range of equivalency ratios for stable combustion, was not specifically explored in this research, the combustion efficiency and combustor outlet temperature variation offer important clues about the success of the combustion. These variables aid in determining the overall stability and efficacy of the combustion process, which aids in the comprehension and improvement of gas turbine engine operation.

$$\mathrm{PF} = \frac{\mathrm{Tmax} - \mathrm{Tave}}{\mathrm{Tave} - \mathrm{Tinlet}} \qquad (7)$$

The maximum temperature (Tmax) at the combustor outlet gives information on the combustor's peak thermal conditions.As opposed to this, Tave is the mass-weighted average-calculated average temperature at the combustor exit. This characteristic provides a more accurate representation of the entire temperature profile at the combustor exit.

Researchers can evaluate the temperature characteristics and heat transmission within the combustor, which are essential elements for assessing the combustion performance, by analysing Tmax, Tave, and Tinlet.

$$(\mathrm{Emission})\mathrm{dry}, 15\%\mathrm{O2} = \frac{(20.9 - 15)(\mathrm{Emissiondry,meas})}{20.9 - \mathrm{O2,dry,meas}} \qquad (8)$$

It is important to note that the experimental results show a lower combustion efficiency (c) than the results of the numerical calculations. This discrepancy can be ascribed to the combustion efficiency calculation's use of the temperature rise approach, which makes use of adiabatic assumptions. Because the experimental process is not adiabatic, the combustion efficiency suffers as a result of lower combustor output temperatures.

VI. Conclusion

An established mathematical model that included the conservation equations for mass, momentum, and energy as well as large eddy simulation (LES) for turbulence modelling was used to carry out the numerical simulations. The findings of the numerical computations were in good agreement with the results of the experimental tests, supporting the validity and dependability of the numerical code employed in this work.Particularly looked at were the combustion efficiency and combustor outlet temperature fluctuation. The experimental findings and the computed values for these parameters were compared, and the absolute variances between the two sets of data were assessed.

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Since the variances were within a reasonable range, the comparisons showed that the numerical simulations correctly reproduced the combustion performance.It should be noted that the experimental combustion efficiency was somewhat lower than predicted by the mathematical models. This can be linked to the experimental process' non-adiabatic nature, which led to poorer combustion efficiency and lower combustor output temperatures.Overall, this study's findings demonstrate how well the numerical model predicts the gas turbine engines' combustion properties. The numerical code can be used for next simulations and analyses because the numerical and experimental results concur.

References:

[1] Foxen, R.; Fitzgerald, J. Environmental and Agricultural Gains from Renewable Natural Gas. Nat. Gas Electr. 2019, 35, 12–18.

[2] Liu, K.; Alexander, V.; Sanderson, V.; Bulat, G. Extension of fuel flexibility in the Siemens Dry Low Emissions SGT-300-1S to cover a Wobbe Index range of 15 to 49 MJ/Sm3 . J. Eng. Gas Turbines Power 2012, 135, 024502.

[3] Forster, P.; Ramaswamy, V.; Artaxo, P.; Berntsen, T.; Betts, R.; Fahey, D.; Haywood, J.; Lean, J.; Lowe, D.; Myhre, G.; et al. Changes in Atmospheric Constituents and in Radiative Forcing; Technical Report; IPCC: Cambridge, UK; New York, NY, USA, 2007.

[4] Abagnale, C.; Camaretti, M.C.; Robbio, R.D.; Tuccillo, R. CFD study of a MGT combustor supplied with syngas. Energy Procedia 2016, 101, 933–940.

[5] Döbbeling, K.; Meeuwissen, T.; Zajadatz, M.; Flohr, P. Fuel Flexibility of the Alstom GT13E2 Medium Sized Gas Turbine. In Proceedings of the ASME Turbo Expo 2008: Power for Land, Sea, and Air, Berlin, Germany, 9–13 June 2008; pp. 719–725.

[6] Liu, K.; Sanderson, V. The influence of changes in fuel calorific value to combustion performance for Siemens SGT-300 dry low emission combustion system. Fuel 2013, 103, 239–246.

[7] Weiland, P. Biomass Digestion in Agriculture: A Successful Pathway for the Energy Production and Waste Treatment in Germany. Eng. Life Sci. 2010, 6, 302–309.

[8] Bulat, G.; Liu, K.; Brickwood, G.; Sanderson, V.; Igoe, B. Intelligent operation of Siemens (SGT-300) DLE gas turbine combustion system over an extended fuel range with low emissions, GT2011-46103. In Proceedings of the ASME Turbo Expo, Vancouver, Canada, 6–10 June 2011.

[9] Asti, A.; Stewart, J.F.; Forte, A.; Yilmaz, E.; D’Ercole, M. Enlarging the fuel flexibility boundaries: Theoretical and experimental application to a new heavy-duty gas turbine (MS5002E), GT2008-50773. In Proceedings of the ASME Turbo Expo, Berlin, Germany, 9–13 June 2008.

[10] Carrera, A.M.; Andersson, M.; Nasvall, H. Experimental investigation of the 4th generation DLE burner concept: Emissions and fuel flexibility performance at atmospheric conditions, GT2011-46387. In Proceedings of the ASME Turbo Expo, Vancouver, Canada, 6–10 June 2011.

[11] Meziane, S.; Bentebbiche, A. Numerical study of blended fuel natural gas-hydrogen combustion in rich/quench/lean combustor of a micro-gas turbine. Int. J. Hydrog. Energy

ISSN: 2094-0343
DOI: https://doi.org/10.17762/msea.v70i1.2504
2019, 44, 15610–15621. [CrossRef] 23. Ren, Z.; Yang, H.; Lu, T. Effects of small-scale turbulence

[12] Liu, K.; Wood, J.P.; Buchanan, E.; Martin, P.; Sanderson, V.E. Biodiesel as an alternative fuel in Siemens dry low emissions combustors: Atmospheric and high pressure rig testing. J. Eng. Gas Turbines Power 2010, 132, 01150.

[13] Liu, K.; Sadasivuni, S.; Parsania, N. Industrial gas turbine engine response and combustion performance to fuel changeovers in compositions and heating values. Fuel 2019, 242, 507–519.

[14] Ren, J.Y.; Egolfopoulos, F.N.; Tsotsis, T.T. NOx emission control of lean methane-air combustion with addition of methane reforming products. Combust. Sci. Technol. 2002, 174, 181–205.

[15] Ren, J.Y.; Qin, W.; Egolfopoulos, F.N.; Mak, H.; Tsotsis, T.T. Methane reforming and its potential effect on the efficieny and pollutant emissions of lean methane-air combustion. Chem. Eng. Sci. 2001, 56, 1541–1549.

[16] Qin, W.; Egolfopoulos, F.N.; Tsotsis, T.T. Fundamental and environmental aspects of biogas utilization for power generation. Chem. Eng. J. 2001, 82, 157–172.

[17] Kishore, V.R.; Duhan, N.; Ravi, M.R.; Ray, A. Measurement of adiabatic burning velocity in natural gas-like mixtures. Exp. Therm. Fluid Sci. 2009, 33, 10–16.

[18] Hwang, D.J.; Park, J.; Oh, C.B.; Lee, K.H.; Keel, S.I. Numerical study on NO formation in CH4 -O2 -N2 diffusion flame diluted with CO. Int. J. Energy Res. 2005, 29, 107–120.

[19] Liu, F.; Guo, H.; Smallwood, G. The chemical effect of CO2 replacement of N2 in air on the burning velocity of CH4 and H2 premixed flames. Combust. Flame 2003, 133, 495–502.

[20] Carrero, M.M.; De Paepe, W.; Bram, S. Does humidification improve the micro-gas turbine cycle? Thermodynamic assessment based on Sankey and Grassmann diagrams. Appl. Energy 2017, 204, 1163–1171.

[21] Ju, Y.; Maruta, K. Microscale combustion: Technology development and fundamental research. Prog. Energy Combust. Sci. 2011, 37, 669–715.

[22] Melo, M.J.; Sousa, J.; Costa, M.; Levy, Y. Flow and Combustion Characteristics of a Low-NOx Combustor Model for Gas Turbines. J. Propuls. Power 2011, 27, 1212–1217.

[23] Bekker, M.; Oechsner, H. Practical experience of using a biogas-powered micro-gas turbine. Landtech. 2010, 65, 136–138