SEMARAK ILMU PUBLISHING

CFD Letters

Journal homepage:
https://semarakilmu.com.my/journals/index.php/CFD_Letters/index
ISSN: 2180-1363

Reacting Flow Characteristics and Multifuel Capabilities of a Multi-Nozzle Dry Low NO_x Combustor: A Numerical Analysis

Mohammad Nurizat Rahman[1,2*], Mohd Fairus Mohd Yasin[2], Mohd Shiraz Aris[1]

[1] Fuels and Combustion, Generation, Generation and Environment, TNB Research Sdn. Bhd., 43000 Kajang, Selangor, Malaysia
[2] High Speed Reacting Flow Research Laboratory (HiREF), School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia (UTM), Johor Bahru 81310, Johor, Malaysia

ARTICLE INFO

Article history:
Received 1 September 2021
Received in revised form 22 October 2021
Accepted 23 October 2021
Available online 19 November 2021

Keywords:
Computational fluid dynamics (CFD); gas turbine; dry low NO_x combustor; combustion; natural gas quality

ABSTRACT

The fluctuating quality of natural gas (NG) in Peninsular Malaysia (PM) makes it challenging for the gas turbine (GT) combustor to meet the combustion performance requirements from the Original Equipment Manufacturer (OEM). Moreover, the gas quality sensitivity is more apparent in modern dry low NO_x (DLN) combustors. Many of the prior combustion investigations were conducted on a modest scale in the laboratory. In actuality, combustion characterizations in complicated DLN combustors are more valuable to the power generation sector. Hence, the current numerical analysis utilized the RANS formulation and a detailed chemistry to examine the impact of ethane (C_2H_6), carbon dioxide (CO_2), and nitrogen (N_2) proportions in NG on combustion characteristics in a multi-nozzle DLN (MN-DLN) combustor, with the support of Modified Wobbe Index (MWI) calculations. Validations were performed using the combustor outlet temperature (COT) from the power plant where the actual MN-DLN combustor is operated, which revealed less than 10 % discrepancy. Qualitative validations were carried out by comparing the burn trace from the actual combustor wall to the predicted results, revealing an adequate Structural Similarity Index (SSIM) of 0.43. From numerical results of flame fronts and COTs, the addition of 20 % diluents (CO_2 and N_2) to NG demonstrated the blowoff risk. When MWIs of Kerteh and the JDA (major NG resources) were used as baselines, MWI ranges of all NG compositions under study surpassed the OEM's ± 5 % limit. The increase in CO_2 proportion results in a wide MWI range, especially when Kerteh is used as the baseline. Therefore, any GTs in PM that have previously been calibrated to use Kerteh's NG are more likely to have combustion instabilities if CO_2 levels in NG suddenly increase. The higher MWI range backs up the current numerical results that showed the deleterious effects of a high CO_2 composition throughout the combustor firing process. However, increasing the amount of C_2H_6 by up to 20 % is predicted to have minor effects on combustion characteristics. Overall, the validated numerical model of the MN-DLN combustor provided critical information about combustion characteristics and multifuel capabilities in respect to the NG quality in PM.

* *Corresponding author.*
E-mail address: izatfariz49@gmail.com (Mohammad Nurizat Rahman)

https://doi.org/10.37934/cfdl.13.11.2134

1. Introduction

The gas turbine (GT) is a technology that is relatively adaptable in terms of accepting variations in the quality of the gaseous fuel that it uses [1]. However, a GT constructed and calibrated to run on a specified fuel quality range will always prefer to operate within the tolerance limitations in exchange for reliability and the highest feasible operational efficiency [1]. With that being said, GTs can only withstand minor changes in fuel compositions, depending on the GT design and the configuration of the hardware and controls, and must be configured for a certain fuel composition range [2]. The combustion characteristics of a GT combustor are sensitive to the quality of natural gas (NG) delivered by the upstream gas pipeline network [1]. The sensitivity to gas quality is noticeably more apparent in modern dry low NO_x (DLN) combustors [1]. While the fuel-lean reacting swirling flows in DLN combustors provide an efficient flame stabilization mechanism as well as a reduction in Nitric Oxides (NO_x) emissions due to the lower peak temperature of lean flames, the flames under these circumstances are prone to combustion instabilities [3]. As a result, the DLN combustor is more susceptible to changes in operating conditions, such as NG quality fluctuations.

Malaysia is one of the countries where fuel gas is supplied entirely from oil and gas fields due to the richness of NG resources in Malaysia [1,4]. The NG composition changes greatly from source to source, as well as from time to time within the same source [5]. Furthermore, a research once shown that the composition of NG is not constant even inside the same pipeline [5]. The main component of NG is methane (CH_4), which has a high calorific value [5]. Ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), nitrogen (N_2), water (H_2O), and carbon dioxide (CO_2) are other elements that have a direct impact on the NG quality [5]. Other gases are frequently present in trace concentrations [5]. These gases present in NG in various proportions depending on the source of the gas supply, the nature of the treatment, and the extent of treatment it has received [5]. The treatment of the raw NG primarily determines the variations in NG quality [1]. The gas processing plants designed to use the heavier hydrocarbons in the gas supply stream would ensure that the treated gas, which would then enter the gas supply network, was stable [1]. With insufficient pre-treatment, a sour-gas source might have a composition with greater diluent constituents [1]. Due to pipeline ballasting regulations, gas networks that inject liquefied NG (LNG) are known to carry heavier hydrocarbons like C_3H_8 or C_2H_6 with greater N_2 than typical [1]. Comingling many of the various types of gas sources would contribute to the GT combustor's difficulty in burning the reactants to achieve the combustion characteristics required by the GT's Original Equipment Manufacturer (OEM) [1]. The variability in NG composition can cause considerable changes in flame temperature and thermodynamic characteristics of burned gases, affecting GT performance and emissions [5]. For the GT operator, the change in NG composition is a condition that can trigger run-backs, which is when the GT reduces its production through automatic controls [1]. The decrease in GT outputs cost operators millions of dollars in income [1]. Therefore, a combustion characterization in a GT combustor at varied NG compositions is critical for providing insights on reacting flow and aerodynamics behavior in a GT combustor, particularly from the DLN combustor.

Computational Fluid Dynamics (CFD) simulations using validated flow and combustion models are one of the methods for implementing combustion characterization in a GT model [6]. The utilization of the Large Eddy Simulation (LES) approach provides a considerably deeper and more accurate insight into the physics of combustion than the Reynolds Averaged Navier–Stokes (RANS) approach [6]. The LES allows for the investigation of extremely complicated combustion issues such as transient ignition behavior and local extinctions, to mention a few [6]. In these circumstances, the LES with advanced combustion models and complex reaction processes provides outstanding agreement with the experimental data [6]. However, the LES is mostly used in laboratory small-scale situations

involving a simple combustor geometry with a single swirler and one fuel nozzle [6 – 11]. Despite the LES feasibility, studies on complex GT combustor layouts are uncommon [6]. Because of the various low NO_x solutions that have been developed, a range of burner shapes and combustor layouts have been created, increasing the combustor's complexity [7]. As a result, modeling flow and combustion in a complicated GT combustor design is more practical and useful to the industrial sector than modeling flow and combustion in a simple combustor geometry. The greatest impediment to LES applications to be used in industries is their high computing costs [6,12]. The LES, it turns out, requires computational meshes with at least tens of millions of nodes and simulation timeframes of many weeks, even for small-scale combustor models [6]. A standard LES is at least 100 times more computationally demanding than RANS formulations [6]. Tyliszczak *et al.,* [6] used a model GT combustor and discovered that the solutions produced using the LES method did not deviate from the experimental results any more than the steady state results obtained using the RANS model. They also discovered that the chemical kinetics had a greater impact than the turbulence model they were using. Therefore, using the RANS formulation with a detailed chemistry mechanism is more applicable for the combustion analysis in a complex multi-nozzle type industrial DLN combustor at various NG compositions.

The current numerical analysis utilizes the RANS formulation and a detailed chemistry mechanism to examine the impact of C_2H_6, CO_2, and N_2 proportions in NG on the combustion characteristics in a multi-nozzle DLN (MN-DLN) combustor. Comprehensive validations are carried out using actual data from the power plant, supported by chemical equilibrium calculations. The representation of a flame front and the predicted combustor outlet temperature (COT) from the numerical analysis were utilized as indicators to analyze the signs of blowoff, as well as the use of the Modified Wobbe Index (MWI) as the fuel gas interchangeability parameter to further support the numerical results.

2. Physical Setup

This study used as-built dimensions from the power plant to develop the three-dimensional (3D) geometry of a MN-DLN combustor. The combustor geometry was simplified to capture important features, while non-critical components were left out to reduce computational expenses. The computational domain of the MN-DLN combustor, as well as the related boundary condition locations, are shown in Figure 1.

The boundary names used on the combustor are presented in Figure 1. The center-nozzle air has one inlet, whereas the multi-nozzle air has eight. The center-nozzle fuel inlet is concentrically positioned with the center-nozzle air inlet, allowing for optimal fuel and air mixing. On the model, there are 70 auxiliary air inlets where a tiny percentage of the incoming air from the compressor will pass through. The swirler is positioned at the center-nozzle region, as shown in Figure 2. At the center of each multi-nozzle air inlet, there is another fuel inlet labeled as the multi-nozzle fuel inlet, as shown in Figure 3.

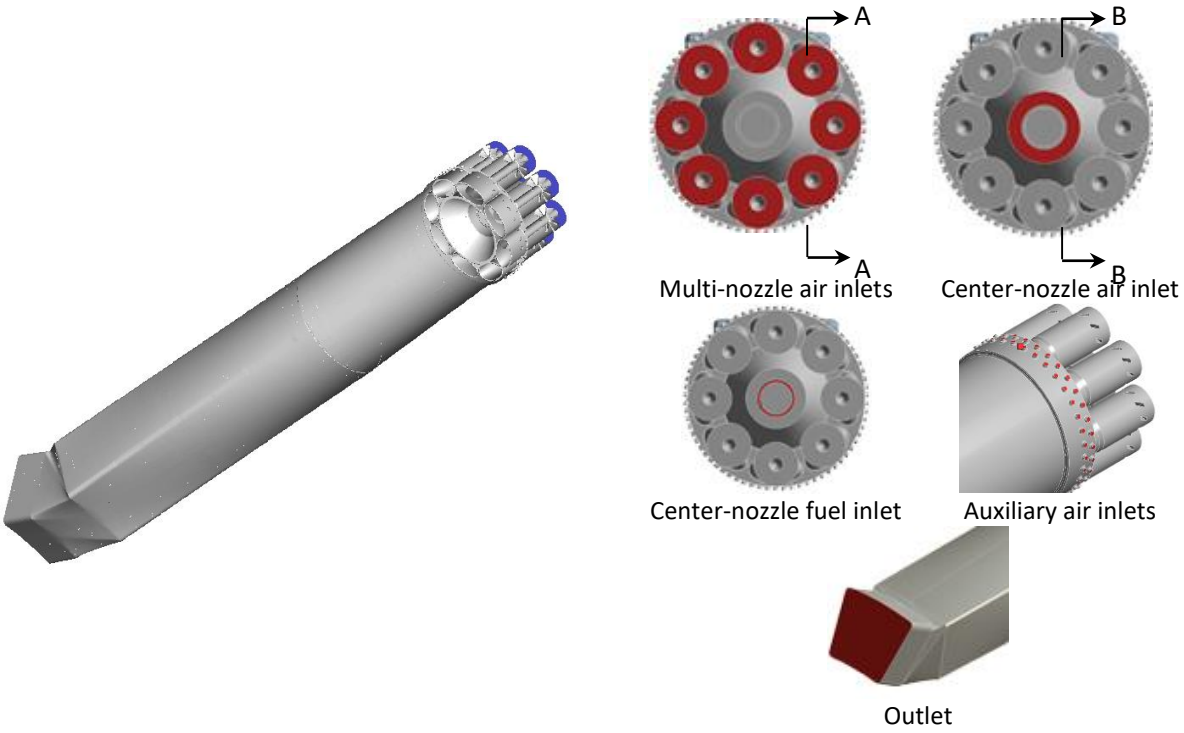


Fig. 1. The computing domain of the modelled MN-DLN combustor showing the internal configurations with the respective boundary condition locations (red color)

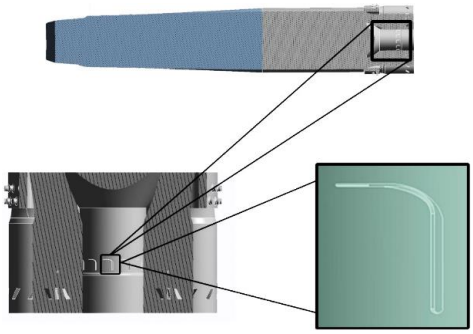


Fig. 2. Swirler location (plane AA)

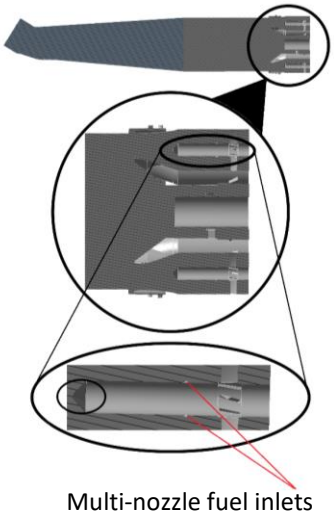


Fig. 3. Multi-nozzle fuel inlets location (plane BB)

3. Numerical Setup

Using a commercial CFD software package, ANSYS Fluent V.19 R1, the governing equations (steady state and compressible) are transformed into discrete forms using the finite volume approach. All setups and numerical processing are done with ANSYS Fluent V.19 R1. The governing equations are solved using the pressure-based solver. The Semi-Implicit Method for Pressure Linked Equations (SIMPLE) technique was adopted to solve the pressure-velocity coupling. Detail information on the constants and formulations utilized in the SIMPLE algorithm can be found in the study of Ferziger *et al.,* [13]. The Discrete Ordinates (DO) model was employed to resolve the radiative heat transfer from the reacting flow.

The probability density function (PDF) and flamelet formulations have previously been demonstrated to be sufficient for modeling the complicated turbulence-chemistry interaction within the combustor [14]. Hence, the current study used the non-adiabatic steady diffusion flamelet model with a detailed chemistry mechanism (GRI Mech 3.0), which computes temperature and species composition using a variable known as the mixture fraction that reflects the local fuel/oxidizer ratio [6]. The mixture fraction is a conserved quantity that obeys the convection-diffusion transport equation [6]. The steady flamelet method describes a turbulent flame brush as a collection of discrete, steady laminar flamelets known as diffusion flamelets. The diffusion flamelets are then embedded in a turbulent flame using statistical PDF methods, allowing for the incorporation of realistic chemical kinetic effects into turbulent flames. The pre-processed and tabulated chemistry saves a lot computational expenses. More information on the constants and formulations utilized in the flamelet approach can be found in Ref. [14].

The NG in this study is examined by a mixture of four different gases, namely CH_4, C_2H_6, CO_2, and N_2. The case studies for examining the influence of varying NG compositions on combustion characteristics in the combustor model are shown in Table 1. The pure CH_4/air flame (B) is used as the baseline scenario. Sets C1-C3 look into the effects of C_2H_6 on combustion properties. The effects of CO_2 and N_2 are then examined in triple gas mixtures, as indicated in sets D1-D4 and E1-E4, respectively. The C_2H_6 proportion in the triple gas mixtures is kept constant at 10 % in order to account for the impact of C_2H_6 as one of the principal components of natural gas.

Table 1
Boundary conditions for each case studies

Parameters	Case studies											
	B	C1	C2	C3	D1	D2	D3	D4	E1	E2	E3	E4
CH_4 (%)	100	95	90	80	88	85	80	70	88	85	80	70
C_2H_6 (%)	0	5	10	20	10	10	10	10	10	10	10	10
CO_2 (%)	0	0	0	0	2	5	10	20	0	0	0	0
N_2 (%)	0	0	0	0	0	0	0	0	2	5	10	20
Multi-nozzle air inlets (kg/s)	9.3											
Center-nozzle air inlet (kg/s)	10.4											
Center-nozzle fuel inlet (kg/s)	0.3											
Auxiliary air inlets (kg/s)	1.0											
Multi-nozzle fuel inlets (kg/s)	0.3											

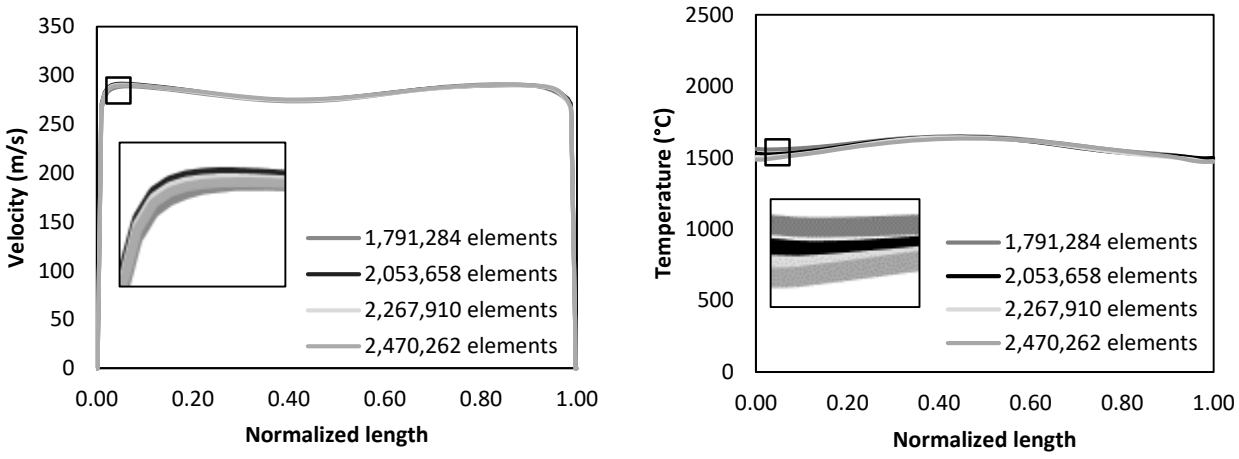
Referring to Table 1, the mass flow rates for all boundary inlets were determined from on-site measurements and the plant data. Despite not being stated in Table 1, the pressure outlet value was chosen based on typical pressure loss values in modern combustors, which range from 2.5 to 5 % of the combustor inlet pressure [15]. Hence, the current analysis assumed a 3 % pressure loss from the overall combustor inlet pressure.

The grid-convergence analysis and validation studies were completed prior to the execution of parametric studies. Plus, different RANS turbulence models were also tested to determine the most suitable RANS model to be applied in the current study based on comparisons with the validation data. In the following section, all of these findings are discussed in further depth.

4. Grid-Convergence Analysis and Model Validation Studies

4.1 Grid Independent Test

The grid independent test is performed to attain a satisfactory spatial convergence accuracy. Meshes (elements) are constructed with orthogonal quality and skewness taken into account to reflect mesh quality, as the level of spatial discretization error is also affected by the mesh quality [16]. The orthogonal and skewness qualities of all generated meshes tested in the grid independent test was controlled to ensure acceptable mesh qualities can be created. Figure 4 shows the velocity and temperature profiles at the combustor outlet center as the mesh number varies. The velocity and temperature profiles nearly no longer varies when the mesh number increases from 2.27 million to 2.47 million, with a variation of less than 1 %. Hence, 2.27 million meshes are chosen for the combustor model.



(a) (b)

Fig. 4. Profiles of (a) velocity and (b) temperature along the center line at the combustor outlet for difference mesh numbers

4.2 Turbulence Model Selection and Validation Studies

Subsequently after the independent mesh number was determined, a model validation exercise was carried out by comparing the quantitative and qualitative results from different RANS turbulence models with the data obtained from the power plant. Table 2 displays the area weighted average velocity and temperature at the combustor outlet for several turbulence models.

Table 2
Area weighted average velocity and temperature for different turbulence models

Turbulence models	Area weighted average		Range of difference (%)	
	Velocity (m/s)	Temperature (°C)	Velocity	Temperature
Standard *k-ε* (standard wall function)	281.37	1527.96	0.8	0.7
Realizable *k-ε* (scalable wall function)	281.07	1520.53		
Transition Shear Stress Theory (SST)	283.33	1525.65		
Reynolds Stress Models (RSM)	282.20	1530.73		

The area weighted averages of velocity and temperature outlets in Table 2 show relatively minor variations as the turbulence model is changed. Small ranges in velocity and temperature outlets have been discovered, with both parameters varying by less than 1 %. As illustrated in Figure 5, the velocity profiles along the center line at the combustor outlet for difference turbulence models were examined to provide detailed insights into the influence of difference turbulence models.

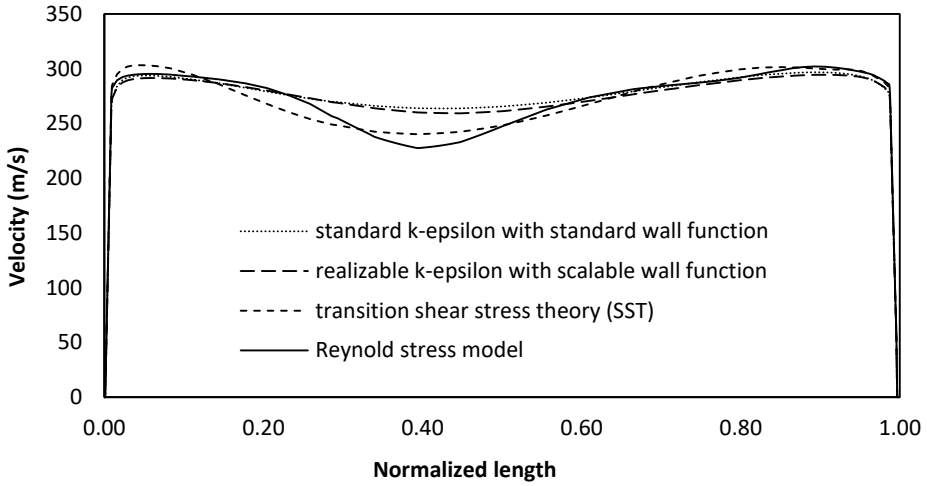


Fig. 5. Velocity profiles along the center line at the combustor outlet for difference turbulence models

Figure 5 shows that the velocity profile differs substantially amongst difference turbulence models, particularly in the central region of the outlet. Because the swirling flow was formed at the center of the combustor, a velocity drop at the center of the outlet is expected. That being said, the velocity drop illustrated in Figure 5 demonstrates the capability of RSM model to capture a greater amount of swirling flow than other turbulence models tested. As a result, Figure 5 demonstrates the ability of RSM model to capture high swirling flow in a stable manner.

As shown in Figure 6, a qualitative comparison was performed by comparing the predicted temperature contour on the inner combustor wall (fluid domain side) for each turbulence model with the actual combustor picture, which depicts the burn trace from the combustor basket wall. As compared to other turbulence models, the RSM model showed the closest similarity to the burn trace from the wall of the combustor basket, particularly in the regions of the center swirler and the wall of the combustor basket (dotted lines in Figure 6). The Structural Similarity Index (SSIM) was calculated between the burn traces predicted from numerical results and the actual burn trace from the combustor basket, with the RSM model showing the highest SSIM of all models evaluated, at 0.43.

In addition to the qualitative comparison with the combustor wall burn trace, quantitative validations were performed to increase confidence in the numerical model. Using the RSM model, the predicted COT, also known as the turbine inlet temperature (TIT), was compared with the TIT from the power plant where the present GT combustor is installed. The TIT was measured in the installed GT combustor system using a thermocouple positioned in the combustor exhaust. In the current numerical model, the TIT reading was taken from the same location. Furthermore, the amount of CO_2 product calculated by the numerical simulation is compared to the amount of CO_2 product computed by the chemical equilibrium calculation to support the model's validity. Table 3 displays all of these outcomes.

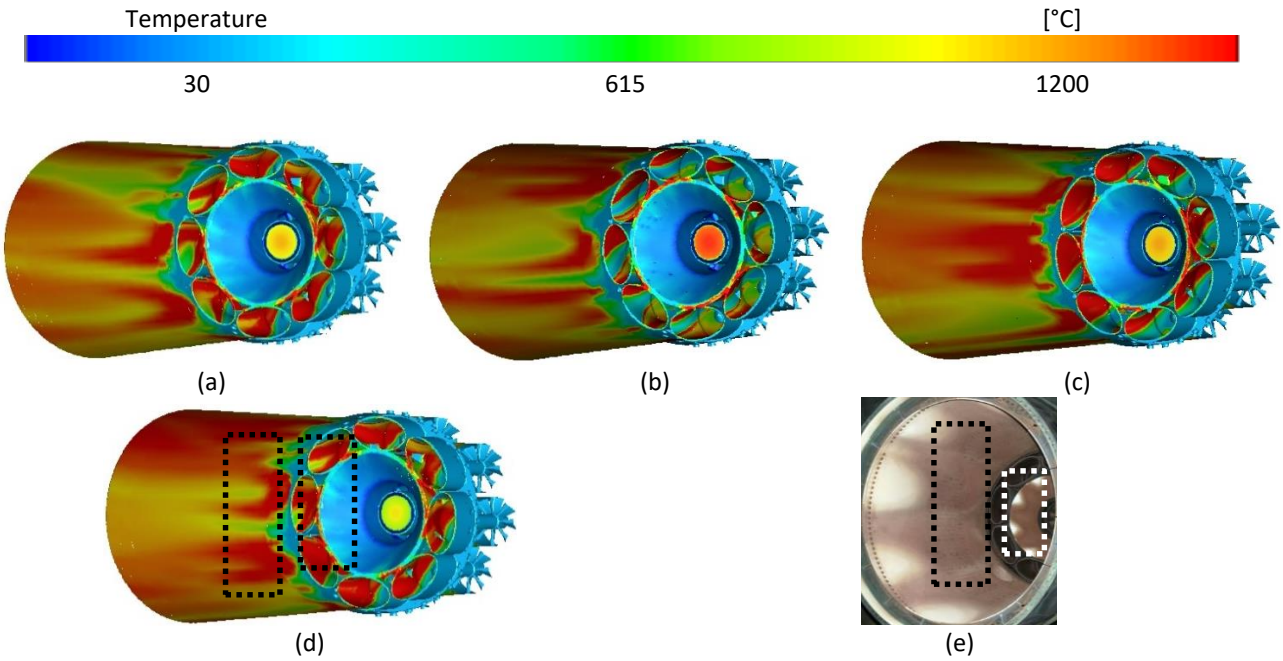


Fig. 6. Combustor wall temperature contours at (a) standard *k-ε* (standard wall function), (b) realizable *k-ε* (scalable wall function), (c) transition SST and (d) RSM models, as well as (e) the actual burn trace from the combustor basket

Table 3
Validations with the TIT (measured) and CO_2 mass fraction (equilibrium) values

TIT			CO_2 (%)		
Actual (°C)	Numerical (°C)	Error (%)	Equilibrium calculation	Numerical	Error
1400	1530	9.3	8.33	8.43	1.2

According to Table 3, the predicted results from the numerical model showed reasonable agreement with the measured TIT and theoretical CO_2 product values with less than 10 % discrepancies. Overall, the reliability of the current numerical model was judged to be satisfactory based on the validation results from qualitative and quantitative comparisons.

5. Results and Discussion

5.1 Predicted Flame Front

In the current study, the flame front was reconstructed using information from the pre-processed flamelet library and the iso-surface approach. In a combustion process, hydroxyl (OH) is a radical species that dominates the chain propagation, chain branching, and chain termination events at varying temperatures [17]. The OH is generated in a zone where extremely exothermic chemical reactions are taking place. As a result, the chemical kinetics of OH in a combustion event allows researchers to incarnate the flame front using the OH generation [18]. Figure 7 depicts the computed values from the flamelet library of OH and temperature profiles.

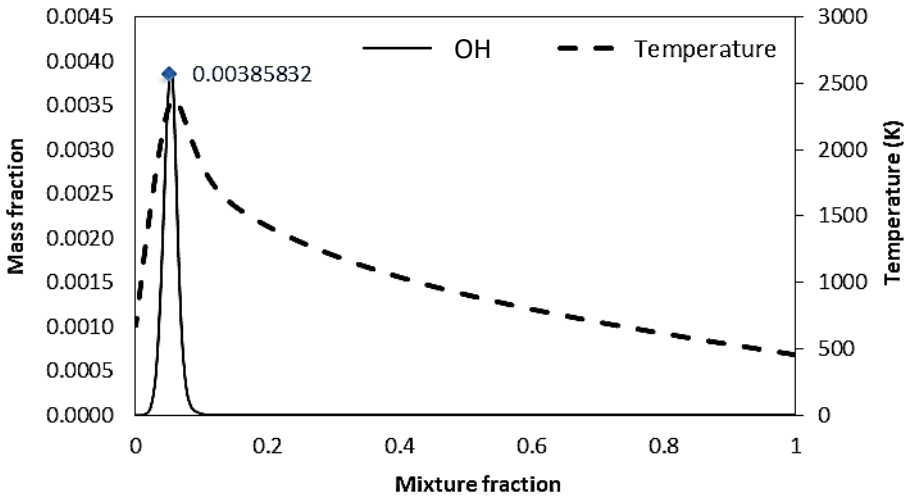


Fig. 7. Computed values from the flamelet library of OH and temperature profiles

Figure 7 shows that the peak of OH generation occurs at the maximum temperature, as depicted in the flamelet file. Hence, the peak mass fraction of OH, 0.0039, is utilized to plot the iso-surface that represents the flame front, as illustrated in Figure 8. The iso-surface was covered by the temperature contour to illustrate the temperature distribution on the produced surfaces. Figure 8 shows the predicted flame front for all of the cases listed in Table 1.

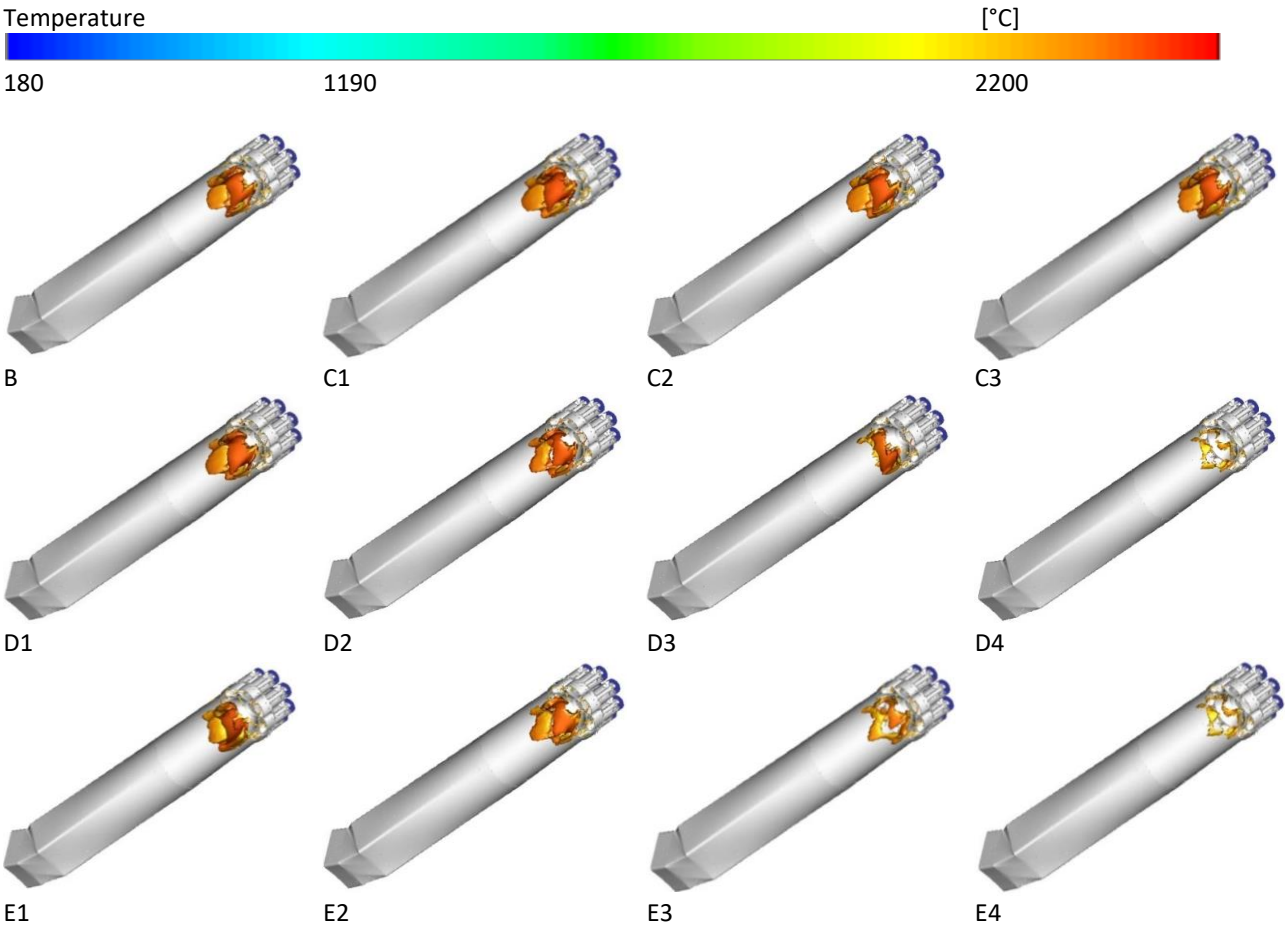


Fig. 8. Predicted flame fronts from all case studies

Figure 8 shows that the flame front sizes in the baseline case and in sets C1-C3 are larger than in all other cases. In the baseline case, the usage of pure CH_4 contributes to the large flame front. While CH_4 has a lower heat of combustion than other hydrocarbons, CH_4 produces more heat per mass than any other organic molecule due to its relatively high hydrogen concentration [19]. The addition of C_2H_6 in sets C1-C3 does not result in a significant reduction in the flame front size. However, the addition of diluents such as CO_2 and N_2 has a substantial impact on the size of the flame front, as seen in sets D1-D4 and E1-E4. Figure 9 provides a deeper understanding of the size of flame front as the amount of C_2H_6, CO_2, and N_2 is varied based on the cases depicted in Figure 8.

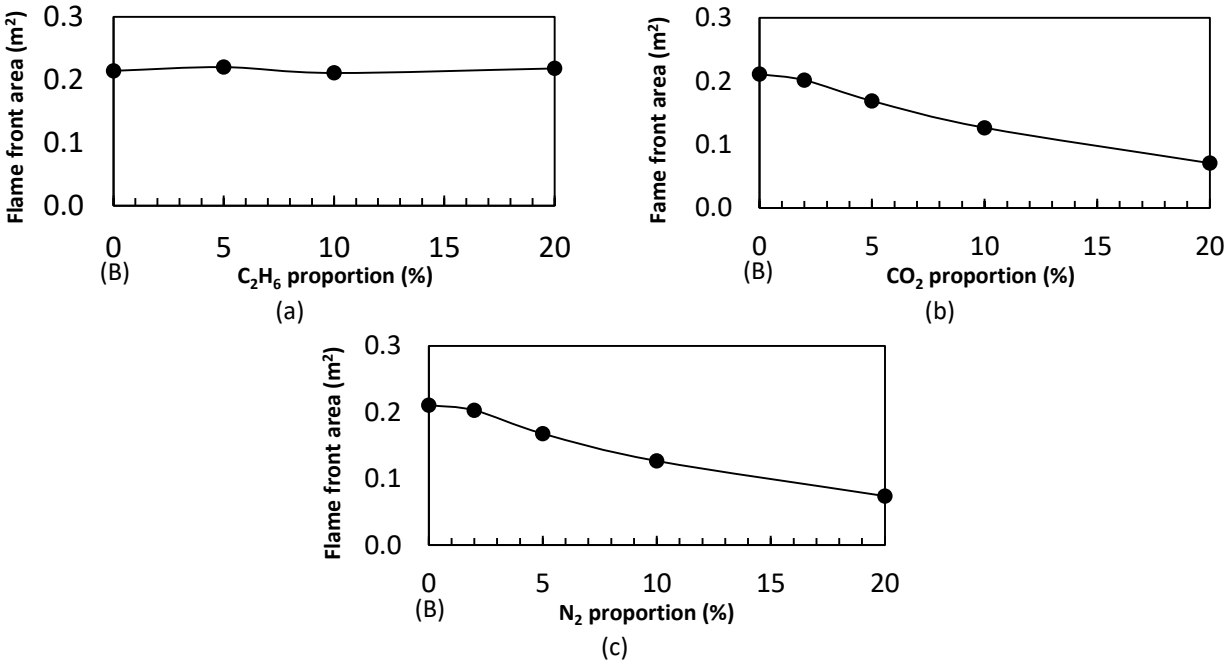


Fig. 9. Flame front areas at varying species proportions in NG

Figure 9 compares the flame front area of the baseline case to that of the other case studies. The flame front area was calculated based on the iso-surface area that represents the flame front, as illustrated in Figure 8. In previous numerical studies, the usage of an iso-surface to represent the flame front was commonly adopted [20]. Referring to Figure 9, with the addition of 20 % CO_2 and 20 % N_2 to the NG composition, the flame sizes are reduced by 67 % and 65 % of the baseline flame front, respectively. The reduction in flame size caused by the addition of CO_2 is slightly greater than that caused by the addition of N_2. The current numerical findings are supported by a prior study by Zheng *et al.,* [21], which found that when CO_2 and N_2 were compared, CO_2 exhibited greater combustion inhibition performance. CO_2 has a larger heat capacity than CH_4 [22]. As a result, CO_2 could function as a diluent, absorbing some of the heat emitted during the reaction and therefore, lessening the combustion intensity [22]. According to Figure 9, the flame size reduction by the inclusion of 20 % diluents has showing signs for a blowoff to occur.

5.2 Combustor Outlet Temperature (COT)

As the presence of C_2H_6 in NG has a negligible effect on the flame front, the current section only analyzes the COT at various CO_2 and N_2 proportions (sets D1-D4 and E1-E4), as shown in Figure 10.

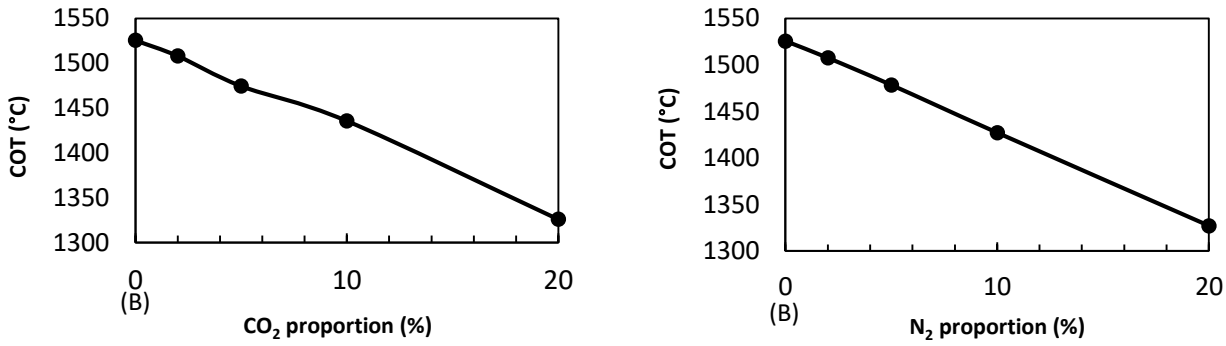


Fig. 10. COTs at varying diluents proportions in NG

Figure 10 shows that adding 20 % CO_2 and 20 % N_2 to the NG composition reduces the COTs by 11.09 % and 11.04 % of the baseline situation, respectively. According to the Guidebook to Gas Interchangeability and Gas Quality by British Petroleum (BP), several experiments have revealed that the COT for the DLN GT combustor can be as low as 1750 K (≈ 1477 °C) and that the blowoff has a high chance to occur if the temperature drops to 1600 K (≈ 1327 °C) [23]. Referring to Figure 10, the addition of 20 % CO_2 reduced the COT to 1326 °C, which is lower than the limit of 1327 °C. The COT was lowered to roughly 1327 °C when 20 % N_2 was added. Hence, the results of COT in Figure 10 verified the flame front results in Figures 8 and 9, where the presence of 20 % diluents indicated the possibility of blowoff.

5.3 Modified Wobbe Index (MWI)

Wobbe Index (WI) determines the interchangeability of fuel gases by measuring the rate of combustion energy generation [23,24]. Mathematically, WI is defined as the ratio of the lower heating value (LHV) to the square root of the specific gravity (SG) of the fuel gases [23,24]. The primary use of WI is to compare the energy released by gaseous fuels of various compositions. Given an equivalent volumetric flow rate, if two gaseous fuels have the same WI, the energy release should be the same. The distinction between WI and MWI is that MWI considers the temperature of the fuel gas. The MWI has been utilized by General Electric (GE), one of the world's largest GT manufacturers, to verify the fuel gas interchangeability [25]. Detail information on the MWI formulations can be found in [23,25].

The majority NG supply in Peninsular Malaysia (PM) comes from Kerteh and the Joint Development Area (JDA) [26]. Table 4 shows the average NG compositions from these two sources [26]. The MWI ranges from all of the NG compositions under study were calculated, with the MWIs of Kerteh and the JDA as the baselines, and the results are shown in Table 5.

Table 4
Natural gas compositions from Kerteh and JDA

Species	Natural gas compositions (%)	
	Kerteh	JDA
CH_4	94	86
C_2H_6	3	5
CO_2	2	7
N_2	1	2

Table 5
Variation in natural gas composition and its associated MWI range

Case	Variability in the composition of natural gas						MWI range (%)
1	Kerteh	B	C1	C2	C3		11
2	Kerteh	B	D1	D2	D3	D4	24
3	Kerteh	B	E1	E2	E3	E4	18
4	JDA	B	D1	D2	D3	D4	19
5	JDA	B	E1	E2	E3	E4	18

GE has specified the MWI range of NG fluctuations that is safe to be used in their heavy-duty GT combustor, which is within a ± 5 % range [25]. Table 5 shows that the MWI ranges for all cases are greater than 5 %. Because of the increase in CO_2 proportion in NG, the MWI range in Case 2 is the largest at 24 %. That being said, any GTs in Malaysia that are already calibrated to use the Kerteh's NG are more likely to have combustion instabilities if the CO_2 content in the NG suddenly spikes. As previously stated in the flame front and COT results, the addition of 20 % CO_2 already indicates the possibility of blowoff. Hence, the high MWI range calculated in Case 2 has further supported the unfavorable effects of a high CO_2 proportion in NG during the MN-DLN combustor firing process.

6. Conclusions

The multifuel capabilities and combustion characteristics in a MN-DLN combustor had been numerically investigated. The predicted TIT from the numerical model has been validated against the actual TIT from the gas-fired power plant where the current combustor is installed, revealing a difference of less than 10 %. The quantitative validation was also supported by the chemical equilibrium calculation of CO_2 product, which revealed a difference of less than 2 % with the predicted data. A qualitative validation was also carried out by comparing the burn trace from the actual combustor with the predicted combustor wall temperature contour, which revealed an adequate similarity when the RSM turbulence model was used. The Structural Similarity Index (SSIM) was calculated between the burn traces predicted from numerical results and the actual burn trace from the combustor basket, with the RSM model showing the highest SSIM of all models evaluated, at 0.43. As a result, all of these validations show that the numerical model based on the RANS formulation and a detailed chemistry mechanism can reasonably predict the combustion characteristics in a MN-DLN combustor.

The impact of various NG compositions on combustion characteristics in the MN-DLN combustor combustor was investigated by varying the C_2H_6, CO_2, and N_2 proportions in NG. The validated numerical model yielded the following insights from all of the NG compositions that were examined

I. The addition of 20 % diluents to NG indicated the risk of blowoff. The inclusion of 20 % CO_2 and 20 % N_2 to the NG composition has been predicted to reduce flame sizes by 67 % and 65 % of the baseline flame, respectively. The addition of 20 % diluents also reduced the COT to around 1327 °C, which is the minimum limit set by the Guidebook to Gas Interchangeability and Gas Quality.
II. When the MWIs of Kerteh and the JDA were put as the baselines, the MWI ranges of all NG compositions under study surpassed the ± 5 % range specified by the OEM. Therefore, a proper calibration towards GTs in PM is required in order to broaden the fuel quality constraints.
III. As opposed to other species under study, the increase in CO_2 proportion in NG results in a greater MWI range, especially when utilizing the MWI from Kerteh as the baseline.

Therefore, any GTs in Malaysia that are already calibrated to use the Kerteh's NG are more likely to experience combustion instabilities if CO_2 levels in the NG suddenly rise. Hence, the increased MWI range from increasing CO_2 proportions has further corroborated the numerical results that demonstrate the negative impacts of a high CO_2 composition in NG during the MN-DLN combustor firing process.

IV. In the current MN-DLN combustor, increasing the amount of C_2H_6 in NG by up to 20 % is expected to have negligible impacts on combustion characteristics.

Acknowledgement
The authors acknowledge the contributions of researchers from HiREF and TNBR, both directly and indirectly, to this study.

References

[1] Chong, Cheng Tung, Jo-Han Ng, Mohd Shiraz Aris, Guo Ren Mong, Norshakina Shahril, Sing Tung Ting, and Meor Faisal Zulkifli. "Impact of gas composition variations on flame blowout and spectroscopic characteristics of lean premixed swirl flames." *Process Safety and Environmental Protection* 128 (2019): 1-13. https://doi.org/10.1016/j.psep.2019.05.015

[2] Abbott, D. J., J. P. Bowers, and S. R. James. "The impact of natural gas composition variations on the operation of gas turbines for power generation." In *Proceedings of the 6th International Conference on the Future of Gas Turbine Technology, Brussels, Belgium*, pp. 17-18. 2012.

[3] Chen, Zhi X., Ivan Langella, Nedunchezhian Swaminathan, Michael Stöhr, Wolfgang Meier, and Hemanth Kolla. "Large Eddy Simulation of a dual swirl gas turbine combustor: flame/flow structures and stabilisation under thermoacoustically stable and unstable conditions." *Combustion and Flame* 203 (2019): 279-300. https://doi.org/10.1016/j.combustflame.2019.02.013

[4] Rahman, Mohammad Nurizat, and Mazlan Abdul Wahid. "Renewable-based zero-carbon fuels for the use of power generation: A case study in Malaysia supported by updated developments worldwide." *Energy Reports* 7 (2021): 1986-2020. https://doi.org/10.1016/j.egyr.2021.04.005

[5] Kayadelen, Hasan Kayhan. "Effect of natural gas components on its flame temperature, equilibrium combustion products and thermodynamic properties." *Journal of Natural Gas Science and Engineering* 45 (2017): 456-473. https://doi.org/10.1016/j.jngse.2017.05.023

[6] Tyliszczak, Artur, Andrzej Boguslawski, and Dariusz Nowak. "Numerical simulations of combustion process in a gas turbine with a single and multi-point fuel injection system." *Applied Energy* 174 (2016): 153-165. https://doi.org/10.1016/j.apenergy.2016.04.106

[7] Nassini, Pier Carlo, Daniele Pampaloni, Roberto Meloni, and Antonio Andreini. "Lean blow-out prediction in an industrial gas turbine combustor through a LES-based CFD analysis." *Combustion and Flame* 229 (2021): 111391. https://doi.org/10.1016/j.combustflame.2021.02.037

[8] Wei, Xutao, Meng Zhang, Zhenhua An, Jinhua Wang, Zuohua Huang, and Houzhang Tan. "Large eddy simulation on flame topologies and the blow-off characteristics of ammonia/air flame in a model gas turbine combustor." *Fuel* 298 (2021): 120846. https://doi.org/10.1016/j.fuel.2021.120846

[9] İlbaş, Mustafa, Serhat Karyeyen, and İlker Yilmaz. "Effect of swirl number on combustion characteristics of hydrogen-containing fuels in a combustor." *International Journal of Hydrogen Energy* 41, no. 17 (2016): 7185-7191. https://doi.org/10.1016/j.ijhydene.2015.12.107

[10] Di Mare, F., W. P. Jones, and K. R. Menzies. "Large eddy simulation of a model gas turbine combustor." *Combustion and Flame* 137, no. 3 (2004): 278-294. https://doi.org/10.1016/j.combustflame.2004.01.008

[11] See, Yee Chee, and Matthias Ihme. "Large eddy simulation of a partially-premixed gas turbine model combustor." *Proceedings of the Combustion Institute* 35, no. 2 (2015): 1225-1234. https://doi.org/10.1016/j.proci.2014.08.006

[12] Rahman, Tariq Md Ridwanur, Waqar Asrar, and Sher Afghan Khan. "An Investigation of RANS Simulations for Swirl-Stabilized Isothermal Turbulent Flow in a Gas Turbine Burner." *CFD Letters* 11, no. 9 (2019): 14-31.

[13] Ferziger, Joel H., Milovan Perić, and Robert L. Street. *Computational methods for fluid dynamics*. Vol. 3. Berlin: springer, 2002. https://doi.org/10.1007/978-3-642-56026-2

[14] Rochaya, David. "Numerical simulation of spray combustion using bio-mass derived liquid fuels." (2007).

[15] Lefebvre, Arthur H., and Dilip R. Ballal. *Gas turbine combustion: alternative fuels and emissions*. CRC press, 2010. https://doi.org/10.1201/9781420086058

[16] e Silva, Valter Bruno Reis, and João Cardoso. *Computational Fluid Dynamics Applied to Waste-to-energy Processes: A Hands-on Approach*. Butterworth-Heinemann, 2020.
[17] Xiao, FengXia, XiaoHui Sun, ZeRong Li, and XiangYuan Li. "Theoretical Study of Radical–Molecule Reactions with Negative Activation Energies in Combustion: Hydroxyl Radical Addition to Alkenes." *ACS omega* 5, no. 22 (2020): 12777-12788. https://doi.org/10.1021/acsomega.0c00400
[18] Sardeshmukh, Swanand, Michael Bedard, and William Anderson. "The use of OH* and CH* as heat release markers in combustion dynamics." *International Journal of Spray and Combustion Dynamics* 9, no. 4 (2017): 409-423. https://doi.org/10.1177/1756827717718483
[19] Schmidt-Rohr, Klaus. "Why combustions are always exothermic, yielding about 418 kJ per mole of O2." *Journal of Chemical Education* 92, no. 12 (2015): 2094-2099. https://doi.org/10.1021/acs.jchemed.5b00333
[20] Wang, Xujiang, Tai Jin, Yongliang Xie, and Kai H. Luo. "Effects of pressure and Karlovitz number on the turbulence-flame interactions in lean premixed H2/air flames." *Fuel* 234 (2018): 1293-1300. https://doi.org/10.1016/j.fuel.2018.07.158
[21] Zheng, Kai, Xufeng Yang, Minggao Yu, Rongjun Si, and Lei Wang. "Effect of N2 and CO2 on explosion behavior of syngas/air mixtures in a closed duct." *International Journal of Hydrogen Energy* 44, no. 51 (2019): 28044-28055. https://doi.org/10.1016/j.ijhydene.2019.09.053
[22] Mameri, Abdelbaki, and Fouzi Tabet. "Numerical investigation of counter-flow diffusion flame of biogas–hydrogen blends: effects of biogas composition, hydrogen enrichment and scalar dissipation rate on flame structure and emissions." *International journal of hydrogen energy* 41, no. 3 (2016): 2011-2022. https://doi.org/10.1016/j.ijhydene.2015.11.035
[23] Wood, Karen, Ieda Gomes, Ben Ho, Steve Kerr, Salli Cavanagh, Doug Wood, and Alan Haywood. "Guidebook to Gas Interchangeability and Gas Quality." (2011).
[24] Liu, Kexin, Pete Martin, Victoria Sanderson, and Phill Hubbard. "Effect of change in fuel compositions and heating value on ignition and performance for Siemens SGT-400 dry low emission combustion system." *Journal of engineering for gas turbines and power* 136, no. 3 (2014). https://doi.org/10.1115/1.4025682
[25] Berkley, D. "Dry Low NOx Combustion Systems for GE Heavy-Duty Gas Turbines." In *ASME*. 1996.
[26] Suruhanjaya Tenaga. "Piped Gas Distribution Industry Statistics 2015." Accessed July 28, 2021.