Simulation of Syngas Addition Effect on Emissions Characteristics, Combustion, and Performance of the Diesel Engine Working under Dual Fuel Mode and Lambda Value of 1.6.

Hussein A. Mahmood1*, Ali O. Al-Sulttani2* and Osam H. Attia1
1Department of Reconstruction and Projects, University of Baghdad, Baghdad, Iraq
2Department of Water Resources Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
E-mail: ali2003ena@uobaghdad.edu.iq

Abstract. The present work aims to study the combustion characteristics related to syngas-diesel dual-fuel engine operates at lambda value of 1.6 operated by five different replacement ratios (RR) of syngas with diesel, which are (10%, 20%, 30%, 40% and 50%). ANSYS Workbench (CFD) was used for simulating the combustion of the syngas-diesel dual-fuel engine. The numerical simulations were carried out on the Ricardo-Hydra diesel engine. The simulation results revealed that the diesel engine's combustion efficiency was enhanced by increasing the diesel replacement with Syngas fuel. The diesel engine's combustion efficiency. The peak in-cylinder temperature was enhanced from 915.9K to 2790.5K (50% RR). Moreover, the peak pressure was improved from 3659073 Pa to 4525366 pa (23% increase), 4947790 pa (35% increase), 5929709Pa (62% increase) and 6708188 Pa (83%) for diesel fuel mode and dual fuel mode (20%, 30%, 40% and 50%) respectively. Moreover, CO, NO, and CO2 emissions in the engine increased with the increase in syngas' replacement ratio with diesel. Besides, the emission levels of NO, CO2 and CO from a diesel engine are lower than a dual fuel engine (syngas-diesel). The NO mass fraction values rise from 2.02505E-19 at diesel mode to 0.000834126 (20% RR), 0.004176854 (30% RR), 0.005021933 (40% RR) and 0.007554865 (50% RR). Moreover, the CO2 mass fraction values increase from 5.90944E-07 at diesel mode to 0.033849446 (50% RR).

Keywords: Diesel engine; dual-fuel engine; syngas; air pollution; computational fluid dynamics (CFD).

1. Introduction
Fossil fuel won't be sufficient for a sustainable global economy with a constant increase in energy demands in the sector of transportation. In addition to the increase in pollution levels compared to the past, further collaboration between local and international levels was created to impose effective emission legislations to control the levels of emission globally. Thus, international environmental policies were created with rules regarding air pollution and other issues related to the environment. Along with the climate change and air pollution concerns, alternate fuels including electric cars, solar power vehicles, methane, hydrogen, fuel cells, hydrogen, biomass, methane, LPG, and syngas were created to reduce the levels of emission from the transportation sector. With the novel advancements in diesel engines' technology, dual diesel fuel (DDF) can be considered a solution for reducing the total level of emissions from diesel vehicles [1-5].

In the technology of DDF, syngas is considered an alternative fuel that is of high importance to researchers. Lately, syngas received significant attention as one of the low-reactivity fuels. The synthesis gas (abbreviated to syngas), referred to as wood gas or producer gas, includes combustible gases that
Different proportions of (N₂, CO₂, CO, H₂, H₂O, and CH₄) might exist. Also, syngas might be created via a process of gasification related to carbon-containing fuels, including natural gas, biomass, coal, and heavy oil [6-11]. Syngas might be converted into power by cutting-edge reciprocating engines, majorly because they are involved in producing distributed energy (DE) and their low-costs and high effectiveness. There is high anti-knock behaviour related to the mixtures of CO and H₂ and thus might be serving as fuels in terms of internal combustion engines. Yet, adding mixtures of CO and H₂ might increase the NO emissions and temperatures within stoichiometric conditions. Thus, these mixtures were suitable for lean-burn applications, in which the excess air moderates the combustion temperatures [12-14].

The major advantage of using syngas as a fuel for generating power was acquired when the syngas utilised in dual-fuel engines operating within compression ignitions with the lean mixture through a pilot injection related to the diesel fuel [15-17]. Certain fuels don't have enough ignition properties for enabling ignition. Thus two fuels should be utilised. In-cylinder conditions activate the ignition regarding primary fuels (commonly gaseous). The pilot diesel fuel will initially be injected in such a condition, leading to ignition and then temperature increase in the combustion chamber. After that, the primary gaseous fuel (that is, syngas) will be ignited with increased chamber temperature following combustion [12, 18]. Also, dual-fuel engines were used for a lot of applications to use gaseous fuels. Majorly, they have modified diesel engines and might be achieving extremely low levels of emission, especially for particulates and smoke. The advantages of dual fuel conversion involve quieter and smoother operations, considerable long engine life between the overhauls, improved safety, and fuel savings. Few researchers tried to add the syngas fuel to a diesel engine to convert the diesel engine to syngas-dual diesel fuel. The combustion characteristics for diesel-syngas fuel mixture with lambda 1.6 is still scarce. The objective of the presented work is to examine the combustion characteristics related to syngas-diesel dual-fuel engine operates at lambda value of 1.6 and five different replacement ratios of syngas with diesel which are (10%, 20%, 30 %, 40 %, and 50%) by using ANSYS workbench 19 (CFD) software.

2. Numerical Setup for Engine Test
Tables 1 and 2 are respectively showing the details of engine and fuel properties. The engine is operated within dual fuel mode with a different substitution ratio for diesel fuel with syngas fuel and excess air value of 1.6, as shown in Table 3. Engine speed (2000 rpm) and intake temperature (298 K) have been constantly taken at atmospheric pressure[19]. The maximum quantity addition through syngas is limited to (50%) due to knocking, as shown in Table 3.

Various techniques might add syngas fuel in a diesel engine to accomplish a dual fuel operation. In this presented work, the mixture of air and syngas is aspirated naturally into the combustion chamber and the air intake. At the same time, the diesel fuel is directly pumped into the combustion chamber. Thus, syngas fuel is specified as a mass fraction with the air in the FLUENT.

The presented study assumes that the cylinder's fresh air includes N₂ and O₂ with 76.80% and 23.20% mass fraction. Moreover, the syngas includes H and CO with a mass fraction of 50% and 50%. Additionally, the substitution ratio of syngas by energy with diesel in dual-fuel engines is given as follows [20]

\[
\text{substitution ratio} \% = \frac{m_{\text{syngas}} \times LHV_{\text{syngas}}}{m_D \times LHV_D + m_{\text{syngas}} \times LHV_{\text{syngas}}} \times 100\%
\]

Where

- \(m_D\) and \(m_{\text{syngas}}\) where the mass flow rates related to diesel as well as syngas fuels in kg/h. \(LHV_{\text{syngas}}\) and \(LHV_D\) were the lower heating values related to diesel as well as syngas in MJ/kg (Table 2). Moreover, the following expression is used for presenting the syngas's mass fraction in the air:
\[ X_{\text{syngas}} = \frac{m_{\text{syngas}}}{m_{\text{syngas}} + m_{\text{air}}} \]  

(2)

Where \( m_{\text{syngas}} \) is the syngas's mass flow rate, and \( m_{\text{air}} \) might be estimated as follows:

\[ m_{\text{air}} = \lambda \cdot AFR_{D,St} \cdot m_D + \lambda \cdot AFR_{\text{syngas}} \cdot m_{\text{syngas}} \]  

(3)

In which \( \lambda \) is the exceeding air, and \( AFR_{\text{syngas}} \) refers to the stoichiometric ratio of air to syngas fuel and \( AFR_D \). \( St \) refers to the stoichiometric ratio of air to diesel fuel that might be acquired from Table 2. The mass fraction related to syngas, \( N_2 \) and \( O_2 \) might be specified in the same manner. The results are indicated in Table 3.

### Table 1. Specifications of the engine [20][21].

| Type of engine | DI diesel |
|----------------|-----------|
| Model of engine | Ricardo Hydra |
| Number of valves | 2 |
| Number of cylinders | 1 |
| Stroke (mm) | 88.9 |
| Bore (mm) | 80.26 |
| Swept volume (lit) | 0.45 |
| The shape of the combustion chamber | bowl in piston |
| Compression ratio | 20.36:1 |

### Table 2. Fuels characteristics [22][23]

| Description | Syngas | Diesel |
|--------------|--------|--------|
| LHV(MJ/Kg) | 17.54 | 42.8 |
| Stoichiometric AFR(Kg/Kg) | 4.58 | 14.5 |
| Density (kg/m³) | 0.60565 | 833–881 |
| Auto ignition temperature | 873–923 | 477–533 |

### Table 3. Mass fraction of syngas, \( N_2 \), and \( O_2 \).

| Fuel type | Syngas substitution ratio (%) | Lambda (\( \lambda \)) | syngas mass fraction (%) | Oxygen Mass fraction (%) | Nitrogen Mass fraction (%) |
|-----------|------------------------------|------------------------|--------------------------|--------------------------|---------------------------|
| Diesel    | 0%                           | 0                      | 0.233                    | 0.227413958              | 0.727345168               |
|           | 20%                          | 0.023974427            | 0.227413958              | 0.748611614              |
|           | 30%                          | 0.32990235             | 0.225313275              | 0.74169649               |
|           | 40%                          | 0.044340115            | 0.222668753              | 0.732991132              |
|           | 50%                          | 0.056642636            | 0.219802266              | 0.723555098              |
| Diesel-syngas | 1.6                     | 0.032990235            | 0.225313275              | 0.74169649               |
|           | 40%                          | 0.044340115            | 0.222668753              | 0.732991132              |
|           | 50%                          | 0.056642636            | 0.219802266              | 0.723555098              |

3. Setup of Engine Simulation

The combustion simulations have been conducted on the single-cylinder diesel engine and a direct injection at various substitution ratios for the diesel fuel with syngas fuel and 1.6 as a lambda value. At the same time, the calculation involves compression and power strokes. Ansys workbench 16.1 was used to create the combustion chamber geometry and meshing domain of the engine. The computational domain consists of the geometry of the combustion chamber without any ports or valves. Besides, FLUENT software V16.1 was utilised for the solution related to governing equations and Post-processing of findings [24][25].
Simultaneously, the model of RNG k-ε was used for modelling turbulence based on [19]. The program depends on the method of pressure correction, and the PISO algorithm is used. Furthermore, the second-order upwind differencing method was utilised for species, turbulence, momentum, energy, and chemical reaction formulas [19]. In the presented work, the implicit approach and pressure-based solver were utilised as per past researches. Concerning spray, a TAB breakup model and a collision model were utilised [26]. The NOx emissions have been modelled using an extended Zeldovich approach. As indicated via Ganesan and Jayashankara [26], there were two approaches utilised here, which creates nitric oxide throughout the combustion process: Thermal NOx and Prompt NOx. The auto-ignition model (Harden burg model) was utilised for calculating the complex chemical kinetics. Furthermore, the auto-ignition was developed using transport equations for certain ignition species.

3.1. Grid generation
First, a test of mesh independence is achieved for the Chamber of Combustion. As indicated in Table 4 and Figure 1, three size different meshes were created. The simulation is achieved at 2000 rpm engine speed and a syngas replacement ratio with diesel of 20%. The simulation was done on the three-size different meshes to show independence. Figure 2 is showing the evaluated cylinder pressure maximum. It has been identified that there isn’t a considerable variation between the 3 meshes. According to the mesh independence test, case 2 is selected as most adequate for the presented work.

| Case   | Elements | Nodes   |
|--------|----------|---------|
| Case 1 | 133176   | 124401  |
| Case 2 | 398887   | 417886  |
| Case 3 | 542565   | 564164  |

Table 4. Nodes and elements ratio utilised for GIT

![Case 1](image1.png) ![Case 2](image2.png) ![Case 3](image3.png)

Figure 1. The three-size different meshes

![Graph](image4.png)

Figure 2. Grid dependence test results

4. Results
There are 5 replacement rations of syngas with diesel that are utilised for studying the impact of adding syngas on the combustion properties of diesel fuel. ANSYS workbench 16.1 is utilised for calculating the
impact of adding syngas on the combustion properties of a diesel engine. Furthermore, the simulation results on the mixture's combustion properties have been studied, as indicated below.

4.1. Pressure

Figure 3 indicates the pressure cycles evaluated in various cases of the numerical test. In the same figure, the results are shown with crank angle degree. Moreover, Figure 4 shows a peak in-cylinder pressure for different syngas additions under lambda value is 1.6. As shown in Figures 3 and 4, with the increase of syngas replacement ratio with diesel, the peak in-cylinder pressure inside the combustion chamber is raised during the stroke of combustion and expansion. Moreover, the peak pressure was improved from 3659073 Pa to 4525366 pa (23% increase), 4947790pa (35% increase), 5929709Pa (62% increase) and 6708188 pa (0.83) for diesel fuel mode and adding syngas in the following amounts, (20%, 30%, 40% and 50%) respectively.

As demonstrated in Figures 3 and 4, the Diesel engine produces the lowest peak in-cylinder pressure compared to the 5 replacement ratio cases with diesel fuel within the diesel syngas dual engine. This lowest peak in-cylinder pressure is because adding gaseous fuel containing hydrogen into the hydrocarbon fuel increases laminar flame speed linearly. The amount related to hydrogen increases in the mix of the fuel. Thus, in-cylinder pressure increases step by step with an increasing replacement ratio compared to a diesel engine.

Figure 5 shows development related to average pressure contour at engine within various syngas addition ratios, and lambda value is 1.6. Figure 5 also illustrates that the engine's pressures increased with the increasing replacement ratio of syngas with diesel. It reaches its maximum rate in Diesel-syngas dual-mode under replacement ratio is 50%.

![Figure 3. In-cylinder pressure curves at a variety of the ratios of syngas addition and 1.6 exceed air.](image)

![Figure 4. The maximum value of pressure inside the engine at various ratios of syngas addition and 1.6 exceed air.](image)
4.2. Temperature

Figure 6 indicates the relationship between the temperature cycles calculated inside the engine and the crank angle degree under various syngas additions, and the value of lambda ($\lambda$) is 1.6. Moreover, Figure 7 shows a peak in-cylinder temperature for different syngas additions under lambda value is 1.6. As depicted in Figures 6 and 7, with the increase of syngas replacement ratio with diesel, the temperature inside the combustion chamber is raised during the stroke of combustion and expansion. Moreover, the peak in-cylinder temperature was enhanced from 915.9K at diesel mode to 2790.5K (50% RR). Figure 8 shows the development of average temperature contour at the engine with different gaseous addition ratios. Figure 8 shows that the combustion temperature, as well as its formation region, is subjected to an increase with the enhancements of syngas in addition to the hydrocarbon fuel. At the same time, it achieved its highest level in diesel syngas pattern within 50% replacement ratio.

Figure 6. Temperature curves within the various ratios of gaseous additions and 1.6 exceed air

Figure 7. The maximum value of temperature inside the engine at various ratios of syngas addition and 1.6 exceed air

|  | 20% | 30% | 40% | 50% | Diesel |
|---|-----|-----|-----|-----|--------|
| 365 | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) | ![Image](image5.png) |
| 375 | ![Image](image6.png) | ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) | ![Image](image10.png) |
| 395 | ![Image](image11.png) | ![Image](image12.png) | ![Image](image13.png) | ![Image](image14.png) | ![Image](image15.png) |

Figure 5. Development of average pressure within various ratios of syngas addition and 1.6 exceed air
20%  30%  40%  50%  Diesel

Figure 8. Development of the mean value of the temperature within various ratios of gaseous addition and 1.6 exceed air

4.3. CO

Figure 9 indicates the relationship between CO emissions calculated inside the engine and the crank angle degree under various syngas additions under the value of lambda (λ) is 1.6. Figure 10 shows the maximum value of CO emissions inside the engine at various syngas addition ratios, and 1.6 exceed air. As demonstrated in Figures 9 and 10, with the increase of syngas replacement ratio with diesel, in-cylinder CO emissions increased during the combustion and expansion strokes. This result is because the syngas consists of 50% hydrogen and 50% CO. therefore, increasing the syngas addition to the diesel-syngas dual-fuel engine increases the syngas fraction in the mixture turn raising the CO emission. The CO mass fraction values rise from 1.28531E-06 to 0.011987214, 0.016495118, 0.022170059 and 0.028321321 for operations of diesel fuel and syngas -diesel dual fuel mode with the syngas replacement ratio (20%, 30%, 40% and 50%) respectively under 200-rpm engine speed and 1.6 lambda value.

Figure 11 shows the development of the average CO emissions contour inside the engine at various ratios of gaseous addition under lambda is 1.6. Figure 11 shows that the emissions of CO as well as its formation region inside the engine subjected to an increase with the enhancements regarding syngas addition to hydrocarbon fuel

As demonstrated in Figures 9, 10 and 11, the Diesel engine produces the lowest peak in-cylinder CO emissions compared to five cases of replacement ratio the syngas with diesel fuel under the diesel-syngas dual engine. This result is because adding gaseous fuel containing CO increasing CO emissions from the engine. Thus, in-cylinder CO emissions gradually increase with the increase in replacement ratio compared with the diesel engine.

Figure 9. CO emissions curves within various ratios of gaseous addition and 1.6 exceed air.
Figure 10. Maximum value related to CO emission inside the engine at various ratios of syngas addition and 1.6 exceeds air

| Replacement ratio | Diesel | 20% | 30% | 40% | 50% |
|-------------------|--------|-----|-----|-----|-----|
| Peak mass fraction of CO | 1.2853E-06 | 0.011987214 | 0.016495118 | 0.022170059 | 0.028321321 |

Figure 11. CO mass fraction development within various ratios of gaseous additions and 1.6 exceed air

4.4. CO₂
Figure 12 indicates the relationship between CO₂ emissions calculated inside the engine, and the crank angle degree under various syngas additions under the value of lambda (λ) is 1.6. Figure 13 shows the maximum value of CO₂ emission inside the engine at various syngas addition ratios, and 1.6 exceed air. As demonstrated in Figures 12 and 13, with the increase of syngas replacement ratio with diesel, in-cylinder CO₂ emissions increase during the combustion and expansion strokes. Moreover, the CO2 mass fraction values increase from 5.90944E-07 at diesel mode to 0.033849446 (50% RR).

Figure 14 shows the development of the Average CO₂ emissions contour inside the engine at various ratios of gaseous addition under lambda is 1.6. Figures 14 also explains that the CO₂ emissions and its formation region inside the engine increases with enhancements of syngas addition into hydrocarbon fuel.

As demonstrated in Figures 12, 13, and 14, the Diesel engine produces the lowest peak in-cylinder CO₂ emissions than five cases of replacement ratio the syngas with diesel fuel under the diesel-syngas dual engine.

4.5. NO
Figure 15 displays nitric oxide variations with crank angle degrees under different replacement ratios and lambda value 1.6. Moreover, the in-cylinder nitric oxides histories for different syngas additions at and lambda value 1.6 are presented in Figures 16. Figures 15 and 16 exhibited that the replacement ratio of syngas with diesel increases, the hydrogen fraction in the air-fuel mixture rises inside the engine. In turn, the combustion temperature was often high, which results in increasing the peak NO emission. Since the
increase of nitrogen oxide is directly proportional to the temperature inside the engine [21]. The NO mass fraction values rise from 2.02505E-19 to 0.000834126, 0.004176854, 0.005021933 and 0.007554865 for operations of diesel fuel and syngas -diesel dual fuel mode with the syngas replacement ratio (20%, 30%, 40% and 50%) respectively under 2000rpm engine speed and 1.6 lambda value.

Figure 15 shows a development related to NO mass fraction contour at the engine at lambda value 1 and various gaseous addition ratios. Figure 15 illustrated that the NO mass fraction related to pollutants and its formation region increases with improved syngas additions to hydrocarbon fuel and reaches the maximal rate at diesel syngas dual fuel mode under a replacement ratio of 50%.

![Figure 12. CO₂ emissions curves within the various ratio of gaseous additions and 1.6 exceed air](image)

![Figure 13. The maximum value of CO₂ emission in the engine at various ratios of syngas addition and 1.6 exceed air](image)

![Figure 14. CO₂ mass fraction development within various ratio values of the gaseous additions and 1.6 exceed air](image)
Figure 15. b NO emissions curves within various ratios of gaseous additions and 1.6 exceed air

Figure 16. The maximum value of NO emission in the engine at various ratios of syngas additions and 1.6 exceed air

![Mass fraction of NO](image)

| Replacement ratio | 20% | 30% | 40% | 50% | Diesel |
|-------------------|-----|-----|-----|-----|--------|
| Mass fraction of NO | 2.02505E-19 | 0.000834126 | 0.004176854 | 0.005021933 | 0.007554865 |

Figure 17. NO mass fraction development of the pollutant within various ratios of gaseous additions and 1.6 exceed air

5. Conclusions
The present study used a direct injection method with a single cylinder for examining the impact of utilising diesel with syngas at various mixture ratios inside a diesel engine under engine speed of 2000 rpm and lambda value of 1.6 by using Computational Fluid Dynamics. The following conclusions are drawn from the simulation results.
The emission levels of NO, CO2, and CO from the diesel engine are lower than the dual-fuel engine (syngas-diesel). Moreover, according to numerical results, their emissions inside the engine increased with increasing the replacement ratio of syngas with diesel fuel under the dual-fuel phase compared to diesel Engines.

According to CFD results, the NO mass fraction values rise from 2.02505E-19 at diesel mode to 0.000834126 (20% RR), 0.004176854 (30% RR), 0.005021933 (40% RR) and 0.007554865 (50% RR). Moreover, the CO2 mass fraction values increase from 5.90944E-07 at diesel mode to 0.033849446 (50% RR). In addition, the CO mass fraction values rise from 1.28531E-06 to 0.011987214, 0.016495118, 0.022170059 and 0.028321321 for operations of diesel fuel and syngas - diesel dual fuel mode with the syngas replacement ratio (20%, 30%, 40% and 50%) respectively under 200-rpm engine speed and 1.6 lambda value.

The combustion efficiency related to the diesel engine is enhanced as the syngas increase. The Diesel engine produces the lowest peak in-cylinder pressure and temperature compared to the 5 cases of replacement ratio the syngas with diesel fuel under the diesel-syngas dual engine. Moreover, the pressures, temperature inside the engine increased with the increasing the replacement ratio of syngas with diesel.

According to numerical results, the peak in-cylinder temperature was enhanced from 915.9K to 2790.5K (50% RR). Moreover, the peak pressure was improved from 3659073 Pa to 4525366 Pa (23% increase), 4947790 Pa (35% increase), 5929709Pa (62% increase) and 6708188 Pa (83%) for diesel fuel mode and dual fuel mode (20%, 30%, 40% and 50%) respectively.

References
[1] Mahmood H A, Adam N M, Sahari B and Masuri S 2018 Development of a particle swarm optimisation model for estimating the homogeneity of a mixture inside a newly designed CNG-H2-AIR mixer for a dual fuel engine: An experimental and theoretic study Fuel 217 131-50
[2] Mahmood H A, Adam N M, Sahari B and Masuri S 2017 Design of compressed natural gas-air mixer for dual fuel engine using three-dimensional computational fluid dynamics modelling Journal of Computational and Theoretical Nanoscience 14 3125-42
[3] Mahmood H A, Adam N M, Sahari B and Masuri S 2017 New Design of a CNG-H2-AIR Mixer for Internal Combustion Engines: An Experimental and Numerical Study Energies 10 1373
[4] Alhamdany A A, Hameed A Q and Salman Q M 2018 Experimental investigation for the removal of toxic gases from vehicle exhaust using non-thermal plasma Journal of Engineering 24 55-70
[5] Nadaleti W C and Przybyla G 2020 NOx, CO and HC emissions and thermodynamic-energetic efficiency of an SI gas engine powered by gases simulated from biomass gasification under different H2 content International Journal of Hydrogen Energy 45 21920-39
[6] Feng S 2017 Numerical Study of the Performance and Emission of a Diesel-Syngas Dual Fuel Engine Mathematical Problems in Engineering 2017
[7] Ali A A M M, Ali K, Kim C, Lee Y, Oh S and Kim K 2019 Numerical Study of the Combustion Characteristics in a Syngas-diesel Dual-fuel Engine under Lean Condition International Journal of Automotive Technology 20 933-42
[8] Kousheshi N, Yari M, Paykani A, Saberi Mehr A and de la Fuente G F 2020 Effect of Syngas Composition on the Combustion and Emissions Characteristics of a Syngas/Diesel RCCI Engine Energies 13 212
[9] Wei L, Li X, Yang W, Dai Y and Wang C-H 2020 Optimisation of operation strategies of a syngas-fueled engine in a distributed gasifier-generator system driven by horticulture waste Energy Conversion and Management 208 112580
[10] Ward C, Goldstein H, Maurer R, Thimsen D, Sheets B J, Hobbs R, Isgrigg F, Steiger R, Madden D R and Porcu A 2020 Making coal relevant for small scale applications: Modular gasification for syngas/engine CHP applications in challenging environments Fuel 267 117303

[11] Karthikeyan S, Periyasamy M and Mahendran G 2020 Assessment of engine performance using syngas Materials Today: Proceedings 33 4142-4

[12] Azimov U, Okuno M, Tsuboi K, Kawahara N and Tomita E 2011 Multidimensional CFD simulation of syngas combustion in a micro-pilot-ignited dual-fuel engine using a constructed chemical kinetics mechanism international journal of hydrogen energy 36 13793-807

[13] Shudo T 2006 An HCCI combustion engine system using onboard reformed gases of methanol with waste heat recovery: ignition control by International hydrogen journal of vehicle design 41 206-26

[14] Li H and Karim G A 2005 Exhaust emissions from an SI engine operating on gaseous fuel mixtures containing hydrogen International Journal of Hydrogen Energy 30 1491-9

[15] Karim G A 2010 Combustion in Gas-fueled Compression Ignition Engines of the Dual Fuel Type Handbook of Combustion: Online 213-35

[16] Copa J, Tuna C, Silveira J, Boloy R, Brito P, Silva V, Cardoso J and Eusébio D 2020 Techno-Economic Assessment of the Use of Syngas Generated from Biomass to Feed an Internal Combustion Engine Energies 13 3097

[17] Ran Z, Hariharan D, Lawler B and Mamalis S 2020 Exploring the potential of ethanol, CNG, and syngas as fuels for lean spark-ignition combustion-An experimental study Energy 191 116520

[18] Stylianidis N, Azimov U, Maheri A, Tomita E and Kawahara N 2017 Chemical kinetics and CFD analysis of supercharged micro-pilot ignited dual-fuel engine combustion of syngas Fuel 203 591-606

[19] Ali R, Raheemah S H and Al-Mayyahi N N 2020 Numerical Analysis of Combustion Characteristics and Emission of Dual and Tri-Fuel Diesel Engine under Two Engine Speeds Jordan Journal of Mechanical & Industrial Engineering 14

[20] Alrazen H A, Talib A A and Ahmad K 2016 A Two-component CFD Studies of the Effects of H2, CNG, and Diesel Blend on Combustion Characteristics and Emissions of a Diesel Engine International Journal of Hydrogen Energy 41 10483-95

[21] Wannatong K, Akarapanyavit N, Siengsanorh S and Chanchaona S 2007 Combustion and knock characteristics of natural gas diesel dual-fuel engine. SAE Technical Paper

[22] Hagos F Y, Aziz A R A and Sulaiman S A 2014 Trends of syngas as a fuel in internal combustion engines Advances in Mechanical Engineering 6 401587

[23] Mahmood H A, Adam N M, Sahari B and Masuri S 2018 Development of a particle swarm optimisation model for estimating the homogeneity of a mixture inside a newly designed CNG-H2-AIR mixer for a dual fuel engine: An experimental and theoretic study Fuel 217 131-50

[24] Fluent A 2012 Theory Guide, Rel. 14.5 ANSYS Inc

[25] Fluent F 2006 6.3user's guide Fluent Inc

[26] Belal T M, El Sayed M M and Osman M M 2013 Investigating diesel engine performance and emissions using CFD Energy and Power Engineering 5