*Power, Energy and Electrical Engineering*
*M. Deng (Ed.)*


*doi:10.3233/ATDE240334*

# Experimental Analysis of a Diesel-Engine Generator Fueled with Syngas and EGR in Dual Fuel Modes

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**Abstract.** Syngas produced from biomass fuels is studied for renewable energy in combustion engines. Syngas used in dual fuel modes can reduce diesel consumption in diesel engines, but exhaust products are increased. Exhaust gas recirculation (EGR) can increase fuel efficiency and decrease exhaust emissions. Therefore, the research aims to study the performance and emission of a diesel-engine generator at 3,000 rpm and various loads, fueled with dual fuel modes by adding syngas, air, and EGR. Syngas was generated from wood pellet by a downdraft gasifier. Flow rates of syngas and air were added at 93 lpm and 86 lpm, respectively. EGR was expanded from 0.36 to 1.92 lpm. The best engine performance in dual fuel modes was found at 3.82 kW. The increase of syngas, air, and EGR flow rates led to the changes of engine performance and exhaust products. Regular diesel combined with syngas-air-EGR blend by increasing syngas, air, and EGR at 93 lpm, 86 lpm, and 0.84 lpm led to the addition of engine performance and the reduction of exhaust emissions. Outstandingly, carbon dioxide, carbon monoxide, nitric oxides, and particulate matter were decreased by 2.98%, 10.08%, 12.64%, and 2.60%, respectively. The regular diesel saving was raised by 43.33% compared with the mode of only regular diesel.

**Keywords.** Dual fuel modes, Engine performance, Exhaust emissions, Regular diesel, Syngas-air-EGR blend

## 1. Introduction

The natural combustion of organic matters is contributing to the serious crisis of climate changes, environmental emissions, and hygiene issues. Especially, the releases of carbon dioxide ($CO_2$) and particulate matter (PM) provoke global warming and human health problems. Thus, biological materials have been applied with external combustion for heating processes and generating electricity in steam turbines. They cannot be directly used for internal combustion engines due to their solid state, but they can be converted to be syngas, consisted of $CO_2$, carbon monoxide (CO), hydrogen ($H_2$), and methane ($CH_4$), by gasification processes via gasifiers [1-3]. Syngas gives less engine performance due to the calorific value lower than petroleum products. It occurs the more

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engine knock, when applied to petrol engines because of the compression ratios lower than 9:1. Syngas used with diesel engines is lower engine knock than petrol engines, since they are generally constructed with compression ratios in the range 14:1 to 22:1. It cannot be directly ignited in these engines due to the high self-ignition temperature of syngas (typically above 500°C). Thus, it is operated with dual-fuel diesel engines [4-6].

The previous studies of dual-fuel diesel combined with increasing syngas in various speeds and loads identified changes of performance parameters, such as brake thermal efficiency (BTE) and brake specific energy consumption (BSEC). Diesel saving was enlarged more than 40%. The exhaust products were highly increased, except nitric oxide (NO) was decreased [6-13]. Therefore, the combinations of increasing syngas and diesel mixed with 20% oxygenate fuels (fatty acid esters and alcohols) were studied. Because diesel blended with 20% oxygenate fuels was similar engine performance to diesel fuel, it was combined with increasing syngas leading to the changes of $CO_2$, CO, black smoke, and PM. BTE and BSEC were different, as based on kinds and percentages of oxygenate fuels and syngas flow rates. Overall, the fuel saving was enlarged more than 25%. The reduction of NO and the addition of CO were shown. $CO_2$ and black smoke were different, when compared with the modes of only diesel and dual-fuel diesel combined with syngas [14-20]. Although oxygenate fuels could control some exhaust emissions, the increase of syngas by restricting air led to the fuel-rich combustion. Some research [21] increased flow rates of air and syngas combined with diesel mixed with 20% fatty acid methyl ester (FAME), which was FAME20, by adjusting pilot fuel injection (PFI) improving engine performance. BTE was increased by 9% and fuel saving was added by 51%. CO, NO, and PM were reduced when compared with the FAME20 combined with syngas without increasing air flow rate. Additionally, the dual-fuel diesel combined with syngas and exhaust gas recirculation (EGR) was examined with a diesel engine at constant speed and various loads and compared with the dual-fuel diesel combined syngas without EGR. It improved the engine performance and reduced the NO and PM levels from adding EGR [22]. Moreover, there were the studies of dual-fuel FAME20 combined with syngas by increasing compression ratio from 12:1 to 18:1 in the diesel engine by testing at constant speed and various loads. The addition of compression ratio until 18:1 used with the dual-fuel FAME20 combined with syngas led to the changes of BTE, $CO_2$, CO, and NO compared with the compression ratio at 12:1 [23].

Although earlier studies proposed the improving exhaust products by using various methods, engine performance was changed. The examination of dual fuel modes from increasing flow rates of syngas, air, and EGR when used with reducing PFI was rarely seen. Currently, renewable biomass fuels used in Thailand mainly come from agricultural wastes, coconut shells, wood chips, and wood pellets [4, 21]. Wood pellets are lower moisture and easier store [4, 5]. Syngas produced form wood pellets through the downdraft gasifier is lower tars than that of other biomass fuels [4, 7]. Therefore, the research work aims to study the characteristics of a diesel-engine generator at a constant speed of 3,000 rpm and various loads by adjusting PFI, fueled by dual fuel modes from increasing flow rates of syngas, air, and EGR.

## 2. Methodology

First of all, syngas was prepared from wood pellet via a closed top downdraft gasifier, as referred from [4, 5]. Wood pellet was fed on the top and air was restricted on the side of this gasifier, shown in Figure 1. An inverter frequency was accelerated to produce the uncleaning syngas (USG), then it was entered to a cyclone to trap dust. Heat exchanger was applied to reduce tar, then it was led to a chimney (No. 1) to investigate the flame ability. After it could ignite, it was sent to a wet scrubber and a sand bed filter for generating the cleaned syngas (CSG). CSG was examined on the flame ability in a chimney (No. 2) again, before it was kept to study the syngas components. They were investigated by a gas chromatographer, composed of 9.5±1.3% of $CO_2$, 24.2±3.0% of CO, 1.7±0.4% of $CH_4$, 13.9±3.1% of $H_2$, and 50.7±2.5% of $N_2$, and calorific value was by 4.75±0.16 MJ/m$^3$. Diesel baseline was regular diesel, fossil diesel mixed with 10% of FAME in local market of Thailand. Regular diesel was investigated under various ASTM standards. Physical properties, such as fuel density at 15 °C (ASTM D1298), kinematic viscosity at 40 °C (ASTM D445), and gross heating value (ASTM D240), were inspected. They were by 831 kg/m$^3$, 3.19 mm$^2$/s, and 45.17 MJ/kg, respectively.

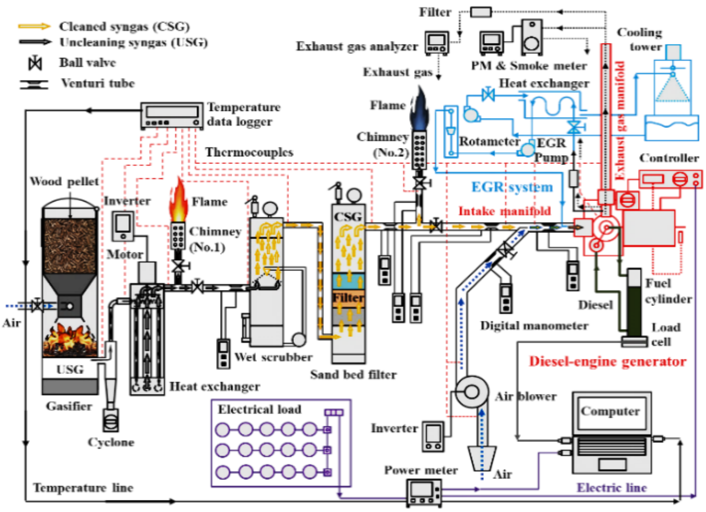


**Figure 1.** Schematic diagram of experimental setup.

After syngas (CSG) came out of the sand bed filter, it was sent to a Y-shaped chamber through a ball valve to mix with air inside an intake manifold. CSG flow was added at 93 lpm and air flow delivered to the intake manifold was increased by 86 lpm, studied from [21]. Flow rates of syngas, air, and syngas-air blends were measured by a venturi tube and a digital manometer. In cases of diesel-engine generator, a high-speed direct injection diesel engine (a single-cylinder and 4-stroke 5GF-ME Mitsuki engine using compression ratio at 18:1) was connected with a generator and an electrical lamp for adding loads. An electrical power was measured by a power meter connected with a computer. Diesel consumption was measured by the fuel weight on load cell over a specified time, recorded by the computer via an Arduino microcontroller. Engine speed and PFI were adjusted on an engine controller. USG, CSG, air, mixture, cylinder wall, exhaust gas, and EGR temperatures were measured by K-type thermocouples and a temperature data logger; all data were acquired on to the computer. The exhaust emissions ($CO_2$, CO, NO, and PM) were recorded by an exhaust gas analyzer and a PM meter. In terms of EGR preparation, exhaust gas coming out of an exhaust manifold was sent into an EGR filter and a heat exchanger combined with a cooling tower. The hot exhaust gas was cooled by heat exchanger, then the cold exhaust gas (EGR) was sucked by an EGR pump into a rotameter and fed into the intake manifold. EGR was increased from 0.36 to 1.92 lpm by the rotameter.

For investigating dual fuel modes, Dual fuel mode A (DF mode A) was dual-fuel regular diesel combined with increasing syngas at 93 lpm and air limited. Dual fuel mode B (DF mode B) was dual-fuel regular diesel combined with increasing syngas at 93 lpm and adding air at 86 lpm via the air blower. Dual fuel mode C (DF mode C) was dual-fuel regular diesel combined with 93 lpm of syngas and 86 lpm of air mixed with increasing EGR at 0.36 lpm. Dual fuel mode D (DF mode D) was dual-fuel regular diesel combined with 93 lpm of syngas, 86 lpm of air, and 0.84 lpm of EGR. Dual fuel mode E (DF mode E) was dual-fuel regular diesel combined with 93 lpm of syngas, 86 lpm of air, and 1.38 lpm of EGR. Dual fuel mode F (DF mode F) was dual-fuel regular diesel combined with 93 lpm of syngas, 86 lpm of air, and 1.92 lpm of EGR.

Experimental procedures began with a warm-up engine about 15 minutes. Syngas (CSG) produced from wood pellet via various processes was prepared. After engine-wall temperature was stable, air temperatures were monitored at 30±5 ºC. The first mode used the only regular diesel (Diesel), when tested by using 3,000±50 rpm and electrical load was added by 20, 40, 60, 80, and 100% for generating the electrical power at 0.95±0.03, 1.91±0.05, 2.86±0.04, 3.82±0.07, and 4.77±0.05 kW, respectively. In each load, various parameters, consisted of powers, fuel-air flow rates, temperatures, and exhaust emissions, were recorded. After finishing the Diesel mode, PFI was reduced by adjusting a fuel injection pump. Subsequently, syngas (CSG) was compressed into the engine cylinder at 93 lpm to increase the engine speed to 3,000±50 rpm, and the DF mode A was investigated at engine-test conditions same as the Diesel mode. After the DF mode A was finished, air flow rate was increased by 86 lpm mixing with syngas flow rate at 93 lpm leading to the engine tests by using DF mode B by using same conditions. After finishing DF mode B, EGR flow rates were added at 0.36, 0.84, 1.38, and 1.92 lpm and blended with flow rates of syngas and air leading to the engine tests by using DF mode C, DF mode D, DF mode E, and DF mode F, respectively. Each mode controlled at 3,000±50 rpm and used the engine-test conditions same as the Diesel mode.

Finally, various parameters, such as flow rates of syngas, air, and EGR, speeds, powers, temperatures, and exhaust emissions, were recorded to triplicate in each condition. Engine tests were more than 100 hours, and these parameters of various modes were calculated in terms of engine performance (BTE and BSEC) and in cases of exhaust emissions ($CO_2$, CO, NO, and PM), studied from [4, 6, 18, 21].

## 3. Results and Discussion

Results of various tests by using dual fuel modes can be explained as follows. In cases of performance parameters, BTE is the ratio of the electrical power output to the total energy input (multiplication of fuel flow rates and calorific value of fuels, such as regular diesel, regular diesel mixed with syngas, and regular diesel mixed with syngas and EGR), studied from [6, 18, 20] and shown in Figure 2(a). BTE was increased with increasing power, and the highest BTE was indicated at 3.82 kW of electrical power due to the lower losses of friction and heat than other powers [4, 21]. Dual fuel modes occurred changes in BTE. Comprehensively, the dual fuel modes had lower BTE than the Diesel mode, decreased by 9.31% (DF mode A) and 7.06% (DF mode F) compared with the Diesel mode. These results were corresponded to [12, 21], because syngas and EGR had lower energy value than regular diesel. The reduction of PFI led to the more displacement of syngas and EGR. Then, total energy consumption supplied to the engine was increased for generating the same power leading to the decrease of BTE [12, 21, 24, 25]. Outstandingly, the dual fuel from mode B to mode F (DF mode B to DF mode F) improved BTE compared with the dual fuel mode A (DF mode A). In cases of adding air flow rate on the DF mode B, the BTE was raised by 1.77%, coinciding with [21]. Because air content was increased for improving fuel-rich combustion, complete combustion was added in burning zones. Especially, non-premixed combustion zone (the main period of injection and combustion of this engine) had more complete combustion resulting the upturn of BTE. Moreover, adding EGR flow rate between 0.36 and 0.84 lpm (DF mode C and DF mode D) occurred the escalation of BTE, expanded up to 5.74% (DF mode D). These results were opposite with [22], illustrated by the compression ratio was appropriate and the air content was sufficient for burning syngas and EGR in diffusive combustion zone resulting the upsurge of BTE [2, 23, 24]. Adversely, enlarging EGR between 1.38 and 1.92 lpm (DF mode E and DF mode F) caused the reduction of BTE. These results were corresponded to [22], due to the uncertain ignitability and incomplete combustion of regular diesel-syngas-EGR blends were increased. Then, regular diesel was more injected in non-premixed combustion zone to produce the same power resulting the total energy consumption increased [2, 25].

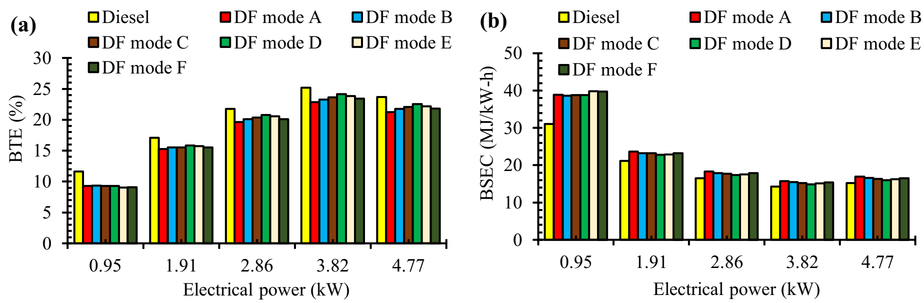


**Figure 2.** Engine performance results.

Figure 2(b) shows the results of BSEC, the ratio of the total energy input to the electrical power output. BSEC was decreased with increasing power, and the lowest BSEC occurred at 3.82 kW of electrical power. These results were conformed by the BTE results. Thus, the best engine performance was found at 3.82 kW. Results and explanations were displayed at this power. The dual fuel modes had higher BSEC than the Diesel mode, enlarged by 10.26% (DF mode A) and 7.58% (DF mode F). These results were consistent with [1, 4, 6, 7], because the less calorific value and the more content of syngas and EGR resulted the total energy input increased for producing electrical power close to that of regular diesel alone leading to the dilation of BSEC. Howbeit, the use of dual fuel from mode B to mode F could reduce BSEC, when compared with the dual fuel mode A. In terms of increasing air flow rate on the DF mode B, the BSEC was reduced by 1.74%, corresponding to [21]. Because the air content was added for mixing with syngas improving the non-premixed combustion phase, it was more complete combustion and the main fuel injection was dropped. Then, the total energy consumption was decreased at same power [15-21]. Importantly, the adding EGR between 0.36 and 0.84 lpm could decrease BSEC, relieved up to 5.41% from using DF mode D. These results were assumed by the air content used in diffusive combustion zone was sufficient for the more syngas-EGR combustion, and then the main regular diesel injection was less. The total energy input was decreased but the electrical power was same leading to the dwindling of BSEC [2]. Nevertheless, the adding EGR between 1.38 and 1.92 lpm (DF mode E and DF mode F) led to the addition of BSEC. These results were supposed by the adding EGR more than 0.84 lpm caused the variability of flame extinction and reignition in non-premixed combustion region. At a result, the main regular diesel injection was augmented to maintain the same power output [2, 22]. The research work investigated the regular diesel saving from using dual fuel modes. Particularly, the DF mode D was more regular diesel saving, increased up to 43.33%. DF mode A and DF mode B expanded the regular diesel saving only 37.35% and 39.54% compared with the Diesel mode, respectively. These results were in line with [21], because the use of only syngas or syngas mixed with EGR decreasing PFI led to the reduction of main injection of regular diesel in diffusive combustion zone. All in all, the research work found that the best engine performance from using dual fuel modes occurred at DF mode D due to the highest BTE and the lowest BSEC.

For measuring exhaust emissions, $CO_2$ was increased with increasing power as identified in Figure 3(a). Comprehensively, the dual fuel modes had lower $CO_2$ than the Diesel mode, dropped by 15.14% (DF mode A) and 25.15% (DF mode F) compared with the Diesel mode at 3.82 kW of electrical power. These results were consistent with [11] but opposite with [6], due to syngas composed of 9.5±1.3% $CO_2$ and 24.2±3.0% CO showing the concentration of CO higher than $CO_2$. Additionally, $CO_2$ released from DF mode A and DF mode B were reduced, and then it was dropped from using EGR. Basically, complete combustion consisted of $CO_2$, vapor water, and nitrogen, but the increase of syngas and EGR contents was more than air element. Therefore, the fuel-rich combustion was raised and the incomplete combustion was increased from air limitation. At a result, carbon element was interacted with the limited oxygen concentration from air surrounding resulting the reduction of $CO_2$ formation [2]. The dual fuel from mode B to mode F changed the $CO_2$ release, when compared with the dual fuel mode A. In cases of adding air flow rate on the DF mode B, the $CO_2$ was explained by 7.94% at 3.82 kW of electrical power, coinciding with [21]. Because the increase of oxygen content from air surrounding led to the more complete combustion in burning zones, the $CO_2$ formation was enlarged. In terms of adding EGR from 0.36 to 1.92 lpm at 3.82 kW of electrical power, the $CO_2$ was reduced up to 11.79% from using DF mode F. The level of $CO_2$ from using DF mode D was decreased by 2.98%. These results were explained by the syngas mixed with adding EGR led to the more fuel-rich combustion, and then they were reacted with a limited oxygen causing the abatement of $CO_2$ [2].

However, CO was reduced with adding power as shown in Figure 3(b). The levels of CO from using dual fuel modes were different, but they had increasingly higher CO than the Diesel mode. CO was increased by 9.33 g/kW-h (DF mode A) and 12.55 g/kW-h (DF mode F), coincided with [16-25]. Because syngas and EGR compositions had very high CO concentration, they resulted the continuous accretion of incomplete combustion in the diffusive combustion zone. Besides, the results of CO were consistent with the $CO_2$ results in previous paragraph. The reduction of $CO_2$ caused the addition of CO. The use of dual fuel from mode B to mode F changed the CO release, when compared with the dual fuel mode A. At 3.82 kW of electrical power, the CO was reduced by 40.27% from adding air flow rate in the DF mode B, corresponding to [21]. Since the air content was escalated for burning the more syngas, the complete combustion was expanded in diffusive combustion zone resulting the abatement of CO. In cases of increasing EGR between 0.36 and 0.84 lpm (DF mode C and DF mode D) could decrease CO, dropped up to 10.08% from using DF mode D compared with the DF mode A. These results were supposed by the amount of air was sufficient for the complete combustion of syngas and EGR. For adding EGR between 1.38 and 1.92 lpm (DF mode E and DF mode F), the CO was increased up to 32.26% from using DF mode F compared with the DF mode A. These results were consistent with [24, 25], since the more incomplete combustion from using insufficient air reacted with the blends of syngas and high EGR resulted the elevated CO emissions.

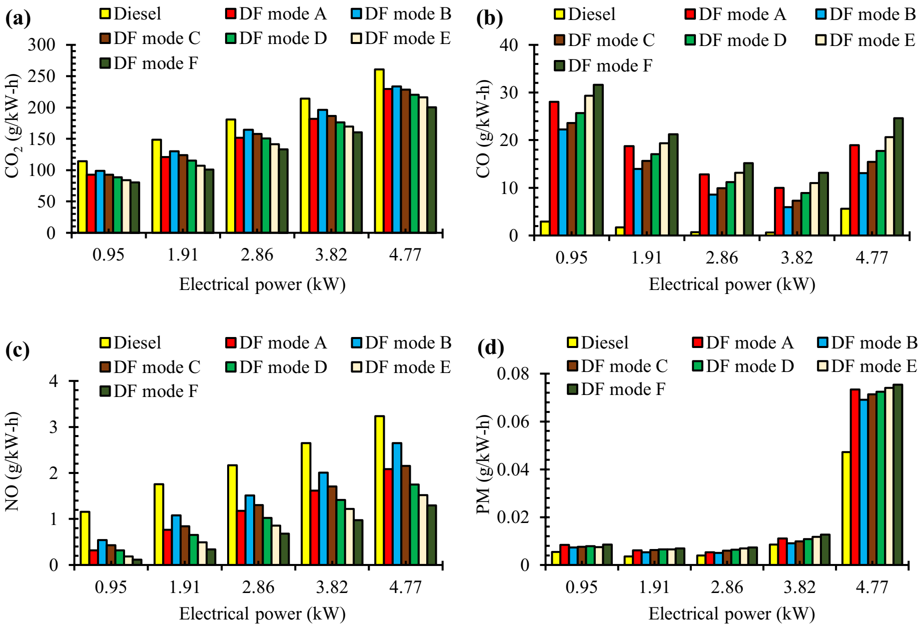


**Figure 3.** Results of measuring exhaust emissions.

Prominently, NO was enlarged with increasing power as reported in Figure 3(c). The releases of NO were different with using dual fuel modes. Overall, the use of dual fuel modes reduced the NO levels. NO was decreased by 39.04% (DF mode A) and 63.20% (DF mode F) compared with the Diesel mode. These results were in line with [4, 12, 17, 21], clarified by the formation of NO depended on the more oxygen content and high flame temperature in combustion zones. The dual fuel modes led to the escalation of incomplete combustion due to the more fuel-rich combustion. At a result, flame temperature was dropped in combustion zones from the oxygen limitation causing the reduction of NO. The use of dual fuel from mode B to mode F changed the NO formation, when compared with the dual fuel mode A. In terms of adding air flow rate in the DF mode B, the NO was increased by 23.09% at 3.82 kW of electrical power, coinciding with [21]. It was illustrated by the accretion of air content was improving the combustion reaction of regular diesel-syngas dual fuel and causing the escalated flame temperature, leading to the increase of NO formation. However, the adding EGR from 0.36 to 1.92 lpm at 3.82 kW of electrical power led to the reduction of NO, decreased up to 39.81% from using DF mode F. The level of NO from using DF mode D was reduced by 12.64%. These results went hand-in-hand with [24, 25], the fuel-rich combustion from using syngas mixed with adding EGR on the dual fuel was highly raised and the air content was burned in a limited range resulting the dwindling of flame temperature. At a result, the NO release was dropped with increasing EGR.

Finally, PM released from diesel engines is mainly formed by CO, smoke, and soot. The results of PM are proved in Figure 3(d). PM was enlarged with increasing power. The levels of PM were different with using dual fuel modes. Notwithstanding, the use of dual fuel modes increased the PM levels compared with the Diesel mode, elongated by 30.92% (DF mode A) and 50.03% (DF mode F). These results were in line with [21, 22], due to the more incomplete combustion from using dual fuel modes resulting the addition of black smoke leading to the escalation of PM. Moreover, the results of PM were consistent with the CO results. The research work found the difference of PM levels from using dual fuel from mode B to mode F, when compared with dual fuel mode A. In cases of adding air flow rate in the DF mode B, the PM was reduced by 10.61% at 3.82 kW of electrical power, in line with [21]. Because the increasing air flow rate led to the escalation of oxygen content reacted with syngas, the more complete combustion was occurred in non-premixed combustion zone leading to the dwindling of PM. In terms of increasing EGR between 0.36 and 0.84 lpm (DF mode C and DF mode D) could reduce PM, decreased by 2.60% from using DF mode D compared with the DF mode A at 3.82 kW of electrical power. These results were supposed by the air content was sufficient for the complete combustion of syngas and EGR leading to the reduction of CO and black smoke [21]. For adding EGR from 1.38 to 1.92 lpm, the PM was escalated up to 14.70% from using DF mode F. These results were explained by the syngas mixed with high EGR flow rate led to the more incomplete combustion, then they enlarged the CO and black smoke emissions leading to the increase of PM [24, 25].

## 4. Conclusions

Experimental analysis of a diesel-engine generator fueled with dual fuel modes from increasing flow rates of syngas, air, and EGR can be summarized as follows.

First of all, the diesel-engine generator fueled with dual fuel modes found the best engine performance appeared at 3.82 kW of electrical power due to the highest BTE and the lowest BSEC. The dual fuel modes had lower engine performance than the Diesel mode. Especially, DF mode A had the less BTE and the more BSEC. BTE was decreased by 9.31% and BSEC was increased by 10.26%. The reduction of PFI was shown at 37.35% compared with the Diesel mode. Exhaust products from using DF mode F found the lowest $CO_2$ and NO, dropped by 25.15% and 63.20%, respectively. The highest CO and PM were identified at 12.55 g/kW-h and 50.03% compared with the Diesel mode, respectively.

For improving DF mode A by increasing air flow rate (DF mode B), the BTE was raised by 1.77% and BSEC was reduced by 1.74% compared with the DF mode A. The abatement of PFI was shown at 39.54% compared with the Diesel mode. Outstandingly, the exhaust emissions were changed. CO and PM were dropped by 40.27% and 10.61%, but $CO_2$ and NO were elongated by 7.94% and 23.09%, respectively. For adding EGR flow rates from DF mode C to DF mode F, they changed the results of performance parameters and exhaust emissions. The best engine performance occurred with the DF mode D. BTE was raised by 5.74% and BSEC was relieved by 5.41% compared with the DF mode A. The best regular diesel saving was identified at 43.33% compared with the Diesel mode. Moreover, the DF mode D improved the exhaust products. $CO_2$, CO, NO, and PM were decreased by 2.98%, 10.08%, 12.64%, and 2.60% compared with the DF mode A, respectively.

Nevertheless, the increase of EGR flow rate more than 0.84 lpm (DF mode E and DF mode F) led to the decrease of engine performance compared with the DF mode D. Particularly, the DF mode F showed the BTE added by 2.49% and the BSEC dropped by 2.43% compared with the DF mode A. The regular diesel saving was shown at 40.61% compared with the Diesel mode. The exhaust emissions from using DF mode F led to the dwindling of $CO_2$ and NO, reduced by 11.79% and 39.81%, respectively. CO and PM were expanded by 32.26% and 14.70% compared with the DF mode A, respectively.

In summary, the research work found the best engine performance and the less exhaust emissions occurred with the DF mode D. Howsoever, the CO and PM from using this mode were higher than the Diesel mode. For investigating in future research, the diesel-engine generator studies by using catalytic converters and electromagnet rearrangement of molecules combined with the DF mode D will be considered for improving engine performance and for reducing CO and PM emissions.

## Acknowledgment

This work was supported by the Faculty of Engineering, Burapha University, Thailand (Grant No. 181/2566) and the Energy Policy and Planning Office (the research funds from the energy conservation promotion, Renewable Energy Plan in 2019), Ministry of Energy, Thailand. Additionally, the authors thank P. Boonprasert, T. Ngamwong, and S. Siripaiboon for their help in recording parameters to complete this study.

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