Effects of Syngas from Various Biomass Gasification on Combustion of Spark Ignition Engine

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ABSTRACT

Syngas compositions vary extensively, depending on biomass properties, oxidant, and gasification conditions. An investigation has been carried out on the GX200 engine fueled by syngas produced through the direct gasification of different solid wastes from agro-forestry production and municipal solid waste, resulting that the engine's indicative cycle work reaches at the highest value of 141 J/cyc in the case of the powered engine by the syngas from wood, then decreases for syngas from municipal solid waste, bagasse, biomass, and rice straw, respectively. The engine's indicative cycle work of the engine fueled by syngas produced from direct gasification of biomass is about 18% lower than that of syngas obtained from RDF. Compared with gasoline fueling mode, when the engine was powered by wood syngas and rice straw syngas, the power derating is 25% and 36%, respectively. In all cases of syngas-fueled engines, NO_x emission is ignored contrasted to the traditional fuels. CO and HC emissions as the engine running at the optimal equivalence ratio of 1.05 and the optimal advanced ignition angle of 35°CA are slightly lower than those of gasoline fueled engine.

1. INTRODUCTION

Syngas includes high thermogenic substances such as H_2, CO, and CH_4; the rest are main impurities such as N_2, H_2O, CO_2, and trace elements such as H_2S, NH_3, HCN (cyanide), HCl, mercury, arsenic, and heavy metals. Usually, syngas contains about 50% of inert gases. When using steam or oxygen as an oxidant, the average low calorific value of syngas is about 10-28 MJ/Nm^3. Meanwhile, if using air as the oxidant agent, the low calorific value of the fuel is about 4-7 MJ/Nm^3 [1]. Therefore, when using syngas as a fuel, the engine power decreases on the one hand, due to the low calorific value of the fuel and on the other hand, due to the reduction in volume efficiency. Using syngas on spark-ignition engines, the power derating can be up to 40-50%, of which 30% is due to a reduction in fuel calorific value [2].

An important fuel characteristic is the laminar flame speed. This parameter depends on the fuel composition, equivalence ratio, pressure, and temperature of the combustion mixture [3],[4]. For syngas, the laminar flame speed is calculated based on the H_2/CO ratio. Once the inert gas content in syngas increases, the laminar flame speed decreases. Because the syngas composition varies over a large range, the laminar flame speed also varies widely. Thus, the advanced ignition angle along with the optimal operating parameters of the engines fueled with syngas or any renewable fuels in general, need to be adjusted flexibly [5],[6].

The quality of syngas depends on the biomass feedstock and gasification conditions. Biomass is very diverse in compositions and properties even the same biomass material. In fact, the heterogeneity of biomass feedstock is one of the disadvantages of gasification process because it is difficult to determine the optimal operating conditions and the end-product characteristics [7]. Therefore, it is very practical to study the relationship between the biomass compositions as well as the gasifier's operating mode and the quality of syngas produced. Sithu Han et al investigated the performance of different biomass species in Myanmar using the numerical model of downdraft gasifier under different operating conditions and showed that different operating conditions such as equivalence ratios and biomass moisture contents have an effect on the syngas composition [8]. vans et al. showed that the H_2 and CO contents of syngas increased with the average gasifier temperature increase from 700 to 980°C [9]. Bingyan et al. revealed that gasification temperature from 400 to 800°C strongly affects biomass yield but when the temperature reached higher than 800°C, this effect decreased [10]. Narváez et al. exposed that the calorific value of syngas decreased with increasing air flow [11]. Devi et al. found that gasifier operating parameters such as temperature and equivalence ratio had a significant effect on tar formation [12]. Controlling these parameters is considered as one of the main methods to reduce these impurity content in syngas. Thus, the

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composition of CO, H_2, CH_4 in the syngas obtained from the gasification process depends on the raw material input as well as the operating parameters of the gasifier. The biomass gasification for power generation plant is a currently popular research trend in Southeast Asia [13] and around the world [14].

The variation in syngas composition will affect the combustion performance and pollutant emission of the engine. This paper focuses on studying the influence of the syngas obtained from the gasification of different types of biomass feedstock delivered by agricultural production on the performance of the spark-ignition engine. This article also compares the effects of syngas obtained from the gasification process of biomass directly and from Refuse-Derived Fuel (RDF) pellet. The research results are aimed at orienting the efficient use of biomass, contributing to reducing greenhouse gas emissions according to the Net Zero strategy.

2. MATERIAL AND METHOD

2.1 Syngas engine

The study was conducted on a syngas engine converted from a Honda GX200 engine with the specifications given in Table 1.

Table 1. Engine Specifications

Engine type	4 stroke, 1 cylinder
Power/speed (kW/rpm)	4.8/3600
Maximum torque/speed (Nm/rpm)	12.4/2500
Cylinder capacity (cm^3)	196
Bore x Stroke (mm)	68 x 54
Advanced ignition angle	20°CA
Compression ratio	8.5 : 1

2.2 Fuel

Two kinds of syngas fuel obtained from gasification of the raw biomass and RDF biomass delivered by different agricultural waste were investigated in this study.

In the simulation CFD Software, we need to put the values of proximate, ultimate and higher heating value analysis of these biomass feedstocks. Then, base on the gasification reactions package available set up in the software, the syngas composition from RDF biomass will be calculated.

Table 2 introduces the syngas composition obtained from the direct gasification process of five different raw materials: rice husk, bagasse, m*unicipal* solid waste (MSW), wood, and common biomass.

Comparing the results from Tables 2 and Table 3, it was found that with the same biomass, if processed into RDF before gasification, the syngas composition would be improved. This is because when producing RDF, the raw materials are mechanically treated, pressed, and heated, resulting in a reduction in the amount of water and other impurities. On the other hand, when pressed into RDF, the material is more homogeneous with a higher density, so the syngas composition is more stable than the syngas obtained from direct gasification.

Table 2. Average composition (%vol) of syngas produced by directly gasification process from different materials

	H_2	CO	CO_2	CH_4	N_2	*Ref.*
Rice husk	13.6	14.9	12.9	2.3	46.1	[15]
Bagasse	16.43	22.61	10.5	0.67	43.34	[16]
MSW	8-23	22-24	6-15	0-3	the rest	[17]
Wood	16-20	17-22	10-15	2-3	the rest	[18]
Biomass	5-16	10-22	8-20	1-6	the rest	[19]

Table 3 presents the syngas composition obtained from RDF gasification of Wheat straw, Bagasse, Coconut shell, Groundnut, Rice husk, and Rice straw.

Table 3. Syngas composition from RDF biomass (%vol) calculated based on simulation [20], [21]

	H_2	CO	CO_2	CH_4	N_2
Wheat Straw	7	20	14	10	49
Bagasse	15	18	16	7	44
Coconut	21	31	5	0.2	42.8
Groundnut	16	26	9	4	45
Rice Husk	20	25	15	3	37
Rice Straw	18	24	11	4	43

2.3 Research Methods

The study was carried out based on CFD Software Ansys Fluent 2021R1. Computational space includes a combustion chamber, cylinder, and intake manifold. Cylinder volume varies with crankshaft rotation angle thus, dynamic meshing was applied in this volume. The grid independency study has been carried out for the calculation space. Effects of grid schemas on variations of the peak pressure of the compression were examined. Five grid schemas were tested: grid 1 (175827 cells), grid 2 (256785 cells), grid 3 (317243 cells), grid 4 (482468 cells) and grid 5 (592873 cells). The result shows that the predicted maximum pressure of the compression process from grid 3, grid 4 and grid 5 schemas are quite close. Hence, 317243 cells were selected to form the optimum number of cells that can be used in the simulation [6].

The system of convection-diffusion equations is closed thanks to the k-e turbulence model. The thermodynamic parameters of the mixture are calculated through the

Partially Premixed Combustion *model*. Once changing fuel, we recalculate the thermodynamic parameter table. As a result, the calculation of boundary conditions will be simplified. At the intake manifold, there is only air, thus the mixture fraction is f = 0. But at the nozzle inlet, there is only fuel, then f = 1. The local equivalence ratio of the mixture could be calculated in terms of fuel composition and oxygen or through f. When the intake process is finished, the intake manifold is deactivated from the cylinder to reduce the calculation time. The specific modeling process was presented in [22].

3. RESULTS AND DISCUSSIONS

3.1 Performance of engine fueled with syngas gasified directly from different biomass feedstocks

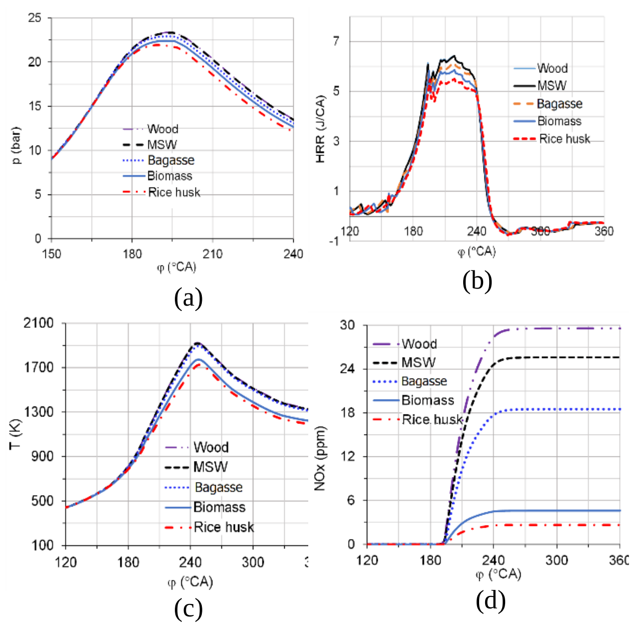

Fig. 1. Effect of syngas on variation of pressure (a), heat release rate (b), temperature (c) and NOx (d) according to crankshaft angle (n=3000 rpm, ϕ=1, φ_s=30°CA).

Fig. 1a presents effects of syngas obtained from the direct gasification of different biomass feedstocks on variation of pressure in the cylinder. Simulation is performed at the engine speed n=3000 rpm, the advanced ignition angle j_s=30°CA, and the equivalence ratio ϕ =1. The results show that when using syngas obtained from wood and municipal solid waste (MSW), we get approximately the same v*ariation curve* of cylinder pressure. This cylinder pressure value is higher than those obtained with syngas from other kinds of biomass. The heat release rate of these two syngas fuels is also higher than those of the others (Fig.1b). This is because the wood has a higher density and a more stable gasification, while municipal solid waste contains substances such as nylon, carton, paper… which have a higher calorific value than other biomass feedstocks. Rice husk has a low density; thus, the received syngas has low energy resulting in a low-pressure curve as well as low combustion temperature (Fig. 1c). The very low concentration of NO_x in the exhaust gas of a syngas-powered engine can be ignored because of the low combustion temperature of the fuel. Although the relative value of NO_x concentration of syngas from wood is higher than the corresponding value of syngas from other biomass, the absolute value is only 30 ppm compared to thousands of ppm NO_x in the exhaust gas of traditional fuel-powered engines (Fig. 2d).

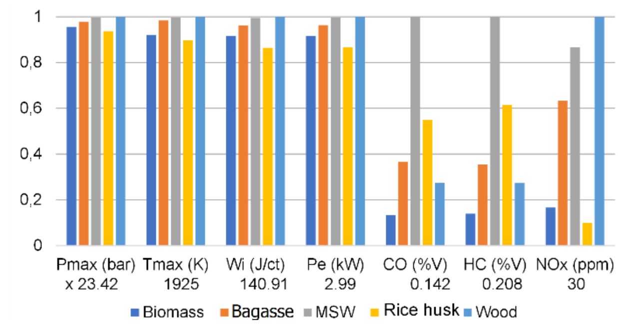

Fig. 2. Comparison of combustion characteristics of the engine fueled with syngas from different types of biomasses

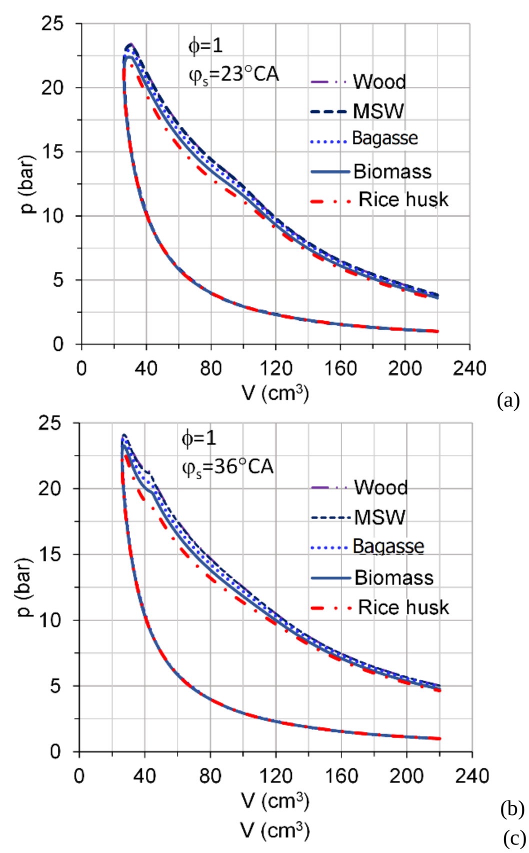

Fig. 3. Effects of equivalence ratio and advanced ignition angle on indicative work diagram of the engine fueled with syngas obtained from gasification of different biomass

Fig. 2 compares the combustion characteristics of the engine fueled by syngas obtained from direct gasification of different types of biomasses. In the case of equivalence ratio ϕ=1, the pollutant emissions of CO, HC, and NO_x are very low, which can be ignored compared with traditional fuels. This is a prominent benefit of using syngas as fuel for internal combustion engines. Under the same operating conditions, the engine's indicative cycle work reached 140.91 J/cyc with syngas production from wood. The value of W_i is in descending order with syngas from MSW, bagasse, common biomass, and rice husk. The power of syngas-powered engines from rice husk is reduced by 14% compared to that from wood-syngas. In comparison with the engine power of gasoline fueled engine of 4.8 kW/3600 rpm (equivalent to 4 kW/3000 rpm), the engine power is reduced by 25% when running on wood syngas and 36% when running on rice husk syngas.

At the same fuel supply conditions and equivalence ratio, when increasing the advanced ignition angle from 23°CA to 36°CA, the maximum cylinder pressure increases, leading to an increase in indicative engine cycle work by 8% for all syngas-fueled engines (Fig. 3a and 3b). If the advanced ignition angle is kept constant at 36°CA, but the equivalence ratio ϕ increases from 1 to 1.1, the maximum pressure changes almost insignificantly (Fig. 3b and Fig. 3c). The simulation results show that the optimal equivalence ratio of syngas-air mixture is by 1.05 and the optimal advanced ignition angle is by 35°CA.

3.2 Performance of engine fueled by syngas gasified from RDF

Fig. 4a and Fig. 4b depict the variations of pressure and temperature with crankshaft angle of the engine fueled with syngas obtained from RDF gasification of different input materials. The results show that the coconut shell syngas generates the highest maximum cylinder pressure and temperature compared to the other investigated fuels. This is due to the syngas obtained from RDF gasification of coconut shell having higher CO and H_2 contents than those of other fuels which results in an improvement of the calorific value of the fuel. Syngas from RDF of rice husk and groundnut bring similar combustion efficiency. Syngas from RDF wheat straw and bagasse are similar in terms of maximum pressure.

Fig. 5a, Fig. 5b, and Fig. 5c compare the variation of pollutants concentrations according to the crankshaft angle when the engine powered with syngas from RDF of different types of biomasses. The results show that at the beginning of the combustion process, the fuel concentration progressively decreases. CO is a component in the syngas but also a component of combustion products. During combustion, CO is generated by the gas-water reaction in thermodynamic equilibrium state. Hence the CO reduction rate (Fig. 5a) is slower than the fuel reduction rate in general (Fig. 5b). Fig. 5c presents the variation of NO_x concentration with crankshaft angle.

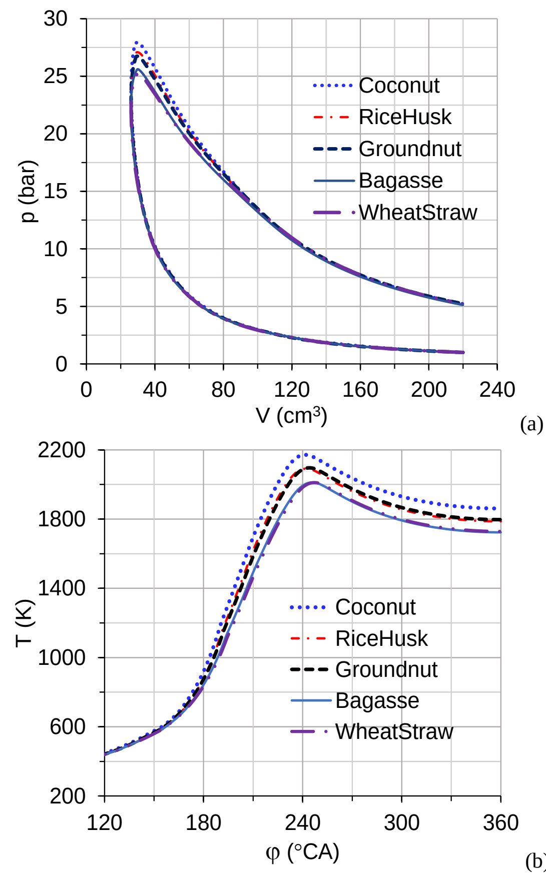

Fig. 4. Effects of RDF-syngas received from different kinds of raw materials on indicative work diagram (a) and on variation of temperature according to crankshaft angle (b) when the engine operates at 3000 rpm, ϕ=1, φ_s =30°CA.

It can be seen clearly that the NO_x emission was similar for syngas from bagasse and wheat straw, about 100 ppm. NO_x concentration in the exhaust gas in the case of syngas from RDF gasification of rice husk and groundnut was similar, equal to about 310 ppm. Syngas from coconut shell emits the highest NO_x quantities because of the highest burning temperature created in this case (Fig. 4b).

Fig. 6 shows that the engine's indicative cycle work in the case of engine powered with syngas from RDF of rice husk and groundnut is 2% lower than that from RDF of coconut shell. The value of W_i of wheat straw and bagasse RDF are 5% and 6% smaller than that of coconut shell RDF, respectively. Emission of CO, HC, and NO_x of syngas from coconut shell RDF gasification reached the highest value. Especially, NO_x concentration of syngas from RDF of coconut shell is 2.5 times higher than that from RDF of rice husk or groundnut and 10 times higher for syngas from RDF of bagasse or wheat straw. Thus, once syngas is used separately, syngas from coconut shell offers the highest indicative engine cycle work but also the largest pollutant emissions. Aiming to harmonize the indicative engine cycle work and pollutant emissions, it is possible to mix syngas from different sources of biomass.

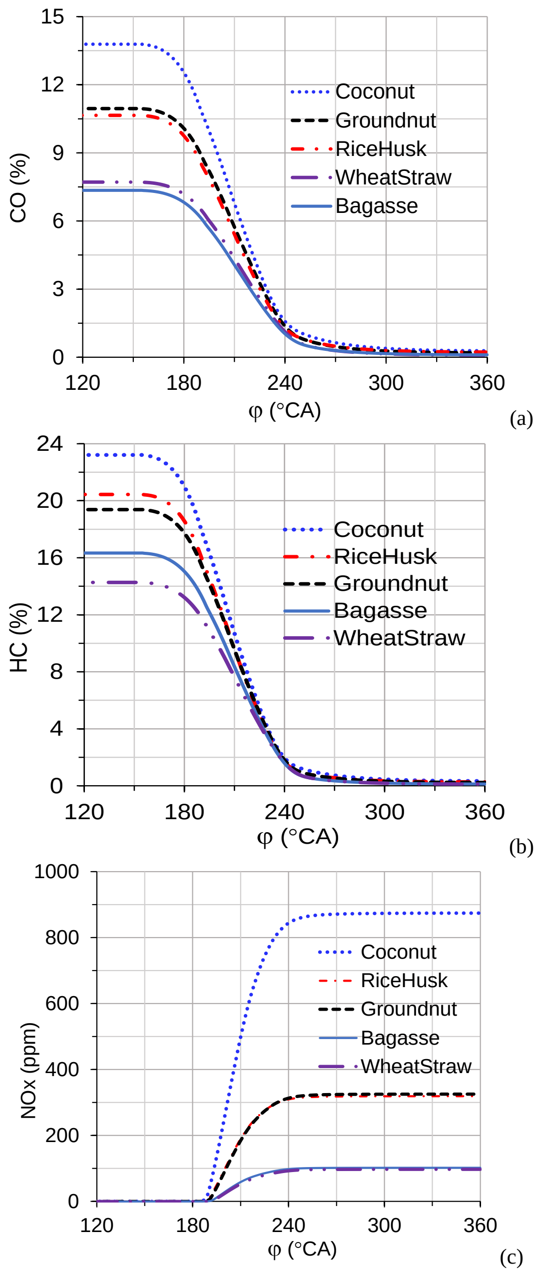

Fig. 5. Variations of CO (a), HC(b), NOx(c) concentration with crankshaft angle when the engine runs at 3000 rpm, ϕ = 1, φ_s = 30°CA on the RDF-syngas received from different kinds of raw materials.

Fig. 7 compares the relative values of combustion characteristics of the engine fueled by syngas from coconut shell RDF, wheat straw RDF and the mixture of syngas obtained from RDF mixed of these two biomasses. It appears that syngas from coconut shell RDF offers the highest value of W_i, temperature, also pollutant concentrations. When switching to syngas from gasification of wheat straw RDF, W_i was reduced by 4%, NO_x emission was reduced by 90%, HC emission was reduced by 60% in comparison when the engine was fueled with syngas from RDF coconut shell gasification. When the engine was fueled by syngas obtained from the mixture of these two RDF, W_i decreases by 1%, NO_x cuts by 70%, HC by 18% compared when the engine was fueled with syngas from coconut shell RDF. As a result, it is beneficial to mix agricultural wastes to produce RDF before gasifying into syngas. The feature of this mixture syngas is that it has low W_i reduction, but very large NO_x reductions compared to syngas produces individual RDF biomass.

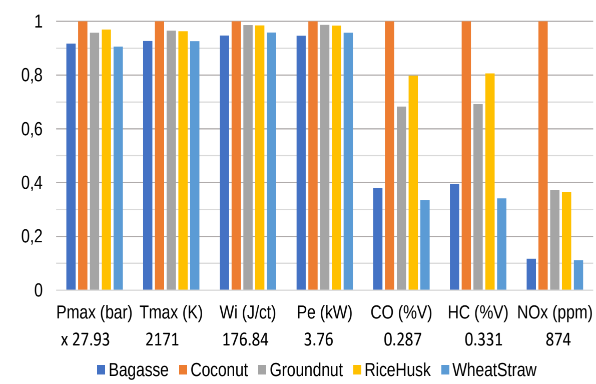

Fig. 6. Comparison of combustion characteristics of the engine fueled with syngas from the gasification of different RDF feedstocks.

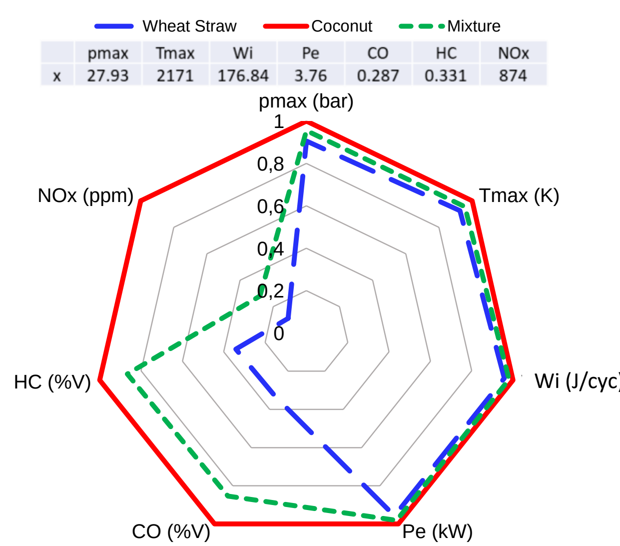

Fig. 7. Comparison of combustion characteristics when syngas powered engine obtained from separate RDF and from the mixture of coconut shell and wheat straw RDF.

4. CONCLUSIONS

The research results allow us to draw the following conclusions:

- Investigating on the Honda GX200 engine powered with syngas produced from direct gasification process of municipal solid waste and wastes from agro-forestry production reveals that the syngas from wood providing the highest engine's indicative cycle work of at about 141 J/cyc. This value decreases in order with syngas from domestic waste, bagasse, common biomass, and rice straw, respectively. The power derating of the engine is by 25% when running on wood syngas and 36% when running on rice straw syngas compared with gasoline fueling mode;

- Syngas obtained from gasification of biomass through RDF has better quality than syngas obtained from direct gasification of biomass. The engine's indicative cycle work in the case of engine fueled with syngas from direct biomass gasification is about 18% lower than that with syngas gasifying through RDF;

- In all cases of syngas-fueled engines, NO_x emission is ignored compared with traditional fuels. CO and HC emissions when the engine running at the optimal equivalence ratio ϕ =1.05 and the optimal advanced ignition angle φ_s=35°CA are slightly lower than those of gasoline fueling engine.

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