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An investigation on utilization of biogas and syngas produced from biomass waste in premixed spark ignition engine

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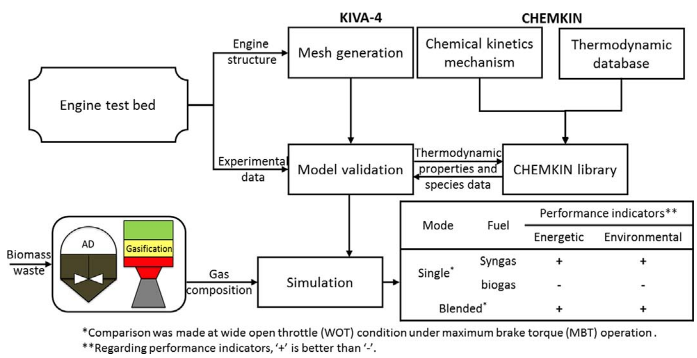
HIGHLIGHTS

- Performance of syngas fueled engine under MBT operation exceeds that of biogas.
- Increase in hydrogen raises the ITE of syngas fueled engine at small ignition advance.
- Advance in ignition timing increases NOx emission for both syngas and biogas fueled engine.
- Increase in methane leads to rise in both ITE and NOx emission for biogas fueled engine.
- Blended-fuel mode can largely lessen the NOx emission and tendency of knock onset.

GRAPHICAL ABSTRACT



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ABSTRACT

Syngas and biogas are two typical biofuels generated from biomass wastes through gasification and anaerobic digestion processes, which are considered to be the future fuels for IC engines. In this work, the utilization of biogas and syngas produced from horticultural waste in a premixed spark ignition engine was investigated. An experimentally validated KIVA4-based CFD simulation integrated with CHEMKIN was performed to evaluate engine performance fuelled by syngas and biogas under both single and blended-fuel modes. Effects of ignition timing, hydrogen content in syngas and methane content in biogas on both energetic and environmental performance have been studied. The indicated thermal efficiency (ITE) of syngas fueled engine at wide open throttle (WOT) condition under maximum brake torque (MBT) operation was found to be higher than that of biogas fueled engine, meanwhile, with much lower NOx emission. In addition, a comparison of the engine performance between the single and blended-fuel modes under different syngas mixing ratios was conducted in terms of ITE and NO_X emission. The results suggest that the utilization of syngas and biogas under blended-fuel mode can not only maintain the MBT energetic performance under single-fuel mode, but also show its potential in reducing NOx emission and lessening the tendency of knock onset.

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Nomenclature

AD	anaerobic digestion
AFT	adiabatic flame temperature
ATDC	after top dead center
B	blended fuel mode
BSFC	brake specific fuel consumption
BTDC	before top dead center
CAD	crank angle degree
CFD	computational fluid dynamics
EVO	exhaust valve opening
HHV	higher heating value
HSAD	high solid anaerobic digestion
HW	horticultural waste
IC	internal combustion
ITE	indicated thermal efficiency
IVC	intake valve closing
MBT	maximum brake torque
MPD	maximum pressure derivative
$\dot{m}$	mass flow rate
NG	natural gas
OECD	organisation for economic co-operation and development
P	power
PoPP	position of the peak pressure
r	ratio
SI	spark ignition
SIE	specific internal energy
TDC	top dead center
WOT	wide open throttle
α	mass fraction

Subscripts

a	after ignition
b	before ignition
bio	biogas
energy	energy ratio
syn	syngas
vol	volumetric ratio

1. Introduction

In order to reduce the dependence on fossil fuels and address the increasing environmental concerns, e.g. greenhouse gas emission, researchers of internal combustion (IC) engine have recently shifted their focus from conventional fossil fuels, e.g. gasoline and diesel, to renewable fuels, e.g. biogas and syngas [1–7]. As predicted by BP energy, by the year of 2035, the fastest fuel growth will be seen in renewables and within OECD countries, renewables will contribute 90% of the net growth in power generation from all sources [8]. Among the renewables, biofuels have been recognized as an energy source with good adaptability that apply equally well to both developed countries as a means of alleviating the environmental burden of reducing carbon emissions, and developing countries by providing electricity in rural areas with great availability of indigenous biomass, e.g. agricultural residues and biomass wastes [9].

Syngas and biogas are two typical biofuels generated from biomass wastes through thermochemical, i.e. gasification, and biochemical, i.e. anaerobic digestion (AD), processes, which are considered as the future fuels for IC engines due to their advantages of high self-ignition temperature, lower production cost, and mature technology. Prior to the utilization in IC engine, impurities in the syngas, e.g. tar and particulates, and biogas, e.g. H_2S and H_2O, should be removed to avoid corrosion problem for downstream utilization [2,10]. After effective purification, a typical molar composition of syngas includes 15–20% H_2, 15–20% CO, 1–5% CH_4, 10–15% CO_2 and the balance N_2, with a higher heating value (HHV) of around 6 MJ/N m^3, as reported from the syngas fuel produced from a gasification system integrated with spark ignition (SI) engine [11]. A typical molar composition of biogas consists of 50–75% CH_4, 25–45% CO_2, 0–10% N_2, 1–2% H_2, and 0–2% O_2, with a HHV of around 25 MJ/N m^3.

Direct use of syngas and biogas in a naturally aspirated IC engine designed for natural gas (NG) usually leads to power derating between 20% and 30% [12,13], attributed to the low HHVs of the gas fuels compared with NG [9] with a HHV of around 39 MJ/N m^3. Therefore, numerous efforts have been spent on improving the calorific value of the input fuels through adding other types of fuels with high HHV into syngas and biogas, e.g. natural gas, diesel, gasoline and hydrogen, so as to minimize the power derating and achieve higher thermal efficiency simultaneously [14–18]. Chandra et al. [14] studied the performance of a stationary diesel engine which was converted into spark ignition mode fueled by compressed NG, NG enriched biogas and biogas. It was found that the NG enriched biogas showed almost similar engine performance as compared to compressed NG in terms of brake power output, specific gas consumption and thermal efficiency. Ji et al. [15] investigated the effect of syngas addition on the performance of a gasoline engine and confirmed that the syngas addition helped improve the indicated thermal efficiency (ITE) and reduce HC, NO_X and particle emissions at lean condition. Rakopoulos et al. [16] conducted availability analysis on a SI engine during the closed part of the engine cycle fueled by biogas and hydrogen blends and revealed that addition of increasing amounts of hydrogen in biogas promoted the degree of reversibility of the burning process. Rinaldini et al. [17] explored the potential of a current automotive turbocharged diesel engine running on both diesel fuel and syngas and found that the use of syngas not only reduced the consumption of diesel oil, but also improved the combustion quality. Shivapuji et al. [18] addressed the influence of mixture hydrogen fraction in syngas on the engine energy balance and the thermo-kinematic response for close to stoichiometric operating conditions. It was observed that the gas to electricity efficiency increased from 18% to 24% as the mixture hydrogen fraction increased from 7.1% to 9.5% and further increase in mixture hydrogen fraction resulted in reduction of efficiency. Despite the advantages mentioned above, most of these technologies consume other fossil fuels, which involve extra cost, require extra storage system, and most importantly, are not environmentally friendly. Furthermore, transportation system for these extra fossil fuels is usually quite limited in rural areas, which have great availability of biomass resource and are considered as the ideal locations for biofuel systems. For this reason, only syngas and biogas fuelled engine has been analysed in this work, without adding other types of fuels.

Hydrogen has been widely identified for its superior combustion characteristics, e.g. high laminar flame velocity, and advantage in clean combustion [16,18]. However, when the hydrogen content in the syngas is too high, unstable combustion, excessive pressure rise and engine knocking may occur, as a result, engine efficiency will largely decrease and engine parts can even be severely destroyed [19,20]. Thus, hydrogen content is recognized as a crucial factor affecting the performance of the syngas fuelled engine, even though the fast flame propagation rate of hydrogen can be slightly moderated by the presence of diluents in the syngas (N_2 and CO_2). Unlike syngas, biogas possesses lower laminar flame velocity and higher ignition energy requirement, as its main compositions are methane and carbon dioxide, leading to a lower combustion rate, for which incomplete combustion may happen for engine application [21]. Thus, an innovative concept of premixing of syngas and biogas in engine operating under blended-fuel mode is