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Waste-to-energy technologies as the future of internal combustion engines

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Syngas has a promising future as alternative to petroleum products and as a fuel for combustion engines. This study provides an overview on the feasibility of using syngas to power internal combustion engines. It presents technological process solutions for producing syngas toward minimizing the formation of tars as the most undesirable component for engine applications.. The combustion process characteristic of syngas composition has been tackled including critical criteria such as the flammability limit, ignition delay, laminar velocity, turbulent velocity, and the subsequent challenges in determining a numerical methods that best matches the experimental datas. The syngas usage as alternative resource, while tackling the uncertainty issue of its composition, for Compression Ignition (CI) and Spark Ignition (SI) with the emission and performance effectiveness has been studied as well. The results of the review showed that syngas can be a viable alternative for some stationary applications, such as advanced integrated systems (ICCG), but its application is, however, relatively limited, for example as a secondary fuel in engines (CI) for automotive applications. However, significant discrepancies between numerical (simulation) and experimental results have been noted. This suggests that there are many scientific and experimental challenges in the area of syngas combustion processes in internal combustion engines. However, given the potential of this group of fuels, especially in the face of the energy crisis, this research is highly desirable and has a significant application perspective.

Key words: *syngas, gasification, physicochemical properties, applications*

1. Introduction

The fast depletion of fossil fuels has resifted the focus towards alternative renewable fuel resources, such as syngas which is produced from biomass or waste [1]. Although current figures show that only 0.5% of syngas is produced from renewable and waste [2], production rate has increased significantly in the recent years with a great prospect for the future as it is expected to grow at 9.3% from 2022 to 2029, reaching nearly US$ 376.7 Bn [3]. This positive trend in the syngas interest was not followed closely by the literature in the past 10 years. Thus there was few researches has been conducted on syngas, and the recently published review papers were mainly referencing more than 10 years old results obtained. In our research we focused on presenting up-to-date results and consolidate the work that has been done by pervious research studies concerning specific topics such as the discrepancy between numerical and experimental results, toward drawing conclusion about the current state of the art in the syngas production and usage.

Currently there is globally almost 2.24 billon tones of municipal waste, and 140 billion metric tons of biomass wastes are generated every year from agriculture, which creates many challenges both on managemental and environmental aspects. As most of the waste goes to landfill, utilizing that waste to produce syngas would produce less emissions than otherwise if would go through incineration while reducing the landscapes allocated for landfills [2].

Gasification and pyrolysis are the main process by which the conversion of the hydrocarbons into syngas is been done, although as efficacy and reliability gasification process standout among all other conversion processes.

Gasification is a thermochemical process where carbonaceous materials conversion into gases occur at elevated temperatures above 600^oC. It is done by breaking the carbon bonds and adding hydrogen to the gaseous product [4]. The conversion process occurs when solid carbon fuel reacts with a gasifying agent such as air, oxygen, water vapor or mixtures of air and water vapor.

In case oxygen or water vapor is used in the gasifying process the product is called medium calorific value gas, or as known simply syngas, which typically having a range of 10 to 20 MJ/Nm^3 heating value. The other name given to the gas product in case of using air as gasifying agent is producer gas, or lower caloric value gas which typically have a heating value range between 4 to 6 MJ/Nm^3 [5].

It produces hydrogen (H_2) and carbon monoxide (CO) mainly, and other components such CO_2, H_2O, tar, hydrogen sulfide, water vapor, hydrocarbon such as methane, and other trace species [6].

The inconsistency in the products of gasification process of waste to produce syngas is particularly difficult to control due to the varying source of the feedstock. Though many solutions are available at the industry such as closely monitoring by infrared sensors the gas composition during the conversion process [7].

The gasification process itself involves multiple complex reaction processes which also contributes to the varying composition of syngas. The generalized and specific chemical reactions involved is presented in the Table 1 [8].

Table 1. Gasification chemical reactions [9]

General chemical reaction:	Hydrocarbon feedstock → $CO(g) + H_2(g) + CO_2(g)$
Char-oxygen reaction	$2C + O_2 \rightleftharpoons 2CO$
Boudouard	$C + CO_2 \rightleftharpoons 2CO$
Steam gasification/water-gas	$C + H_2O \rightleftharpoons CO + H_2$
Methanation	$C + 2H_2 \rightleftharpoons CH_4$
Shift reaction	$H_2O \rightleftharpoons H_2 + CO_2$

Other factors that affect the production of syngas from waste feedstock are residence time, temperature, pressure and the atmosphere during the gasification process. All above factors along with the varying feedstock composition and the complex gasification chemical process can be handled using many solutions that will be tackled in the following chapter.

The syngas can be use as intermediary to produce other chemicals, or for direct usage as fuel, the latter is our topic of concern. From integrated gasification combined cycle (IGCC) to internal combust engines (ICE) there is a wide range of application for syngas.

The technology of using syngas from biomass is relatively old, during WWII when there was shortage of gasoline, wood gas vehicles reached almost 7 million vehicles with countries like Sweden, Germany France and Denmark were on top of producers list. The technology was disregarded as there was a boom in gasoline availability. Strict environmental regulation and phasing out the use of fossil fuels revived the interest in synthetic gases [10–12].

In power generation/syngas has a very promising futures some studies suggest that typical incinerators of 1 tone of waste can produce 530 kWh, gasification system with integrated generation can produce from 650 kWh up to 1100 kWh [13].

2. Waste to syngas production solutions

Different types of gasification process can be achieved depend on the design and intended quality and content of the product. Since feedstocks vary significantly thus the product outcome, it’s of a high importance to select the right gasifier to insure a consistency of the gasification product with minimal contamination and reduced tar output values.

The varying composition of the waste feedstock and the chemical process complexity of gasification presented challenges that is been overcame by the introduction of multiple solutions that would ensure the consistency of the gasification products and removal of impurities such as tar, Sulphur and particulate matter, etc.)

Tar is a condensable hydrocarbon formed of single and multiple aromatics compounds along with polycyclic aromatic hydrocarbons. The challenge of removing tar from the syngas product is one of the main challenges that need to be overcome in order to make the valorization technologies such as syngas production through gasification economically feasible [14].

The tar can lead to engine fouling and catalyst deactivation due to polymerization characteristics and condensation [15].

A number of solutions has been proposed in order to reduce the tar content during the gasification process. For instance, injecting CO_2 during gasification process can reduce the tar formation resulting in close to zero CO_2 process [16].

Typically, there is four types of gasifiers: updraft and downdraft fixed bed, bubbling or circulating fluidized bed reactors. Figure 1 show the principle upon which the four gasifiers work.

Each type of gasifiers has its own advantages and disadvantages which will be presented. Along with the results of some studies that tackled the issue of tar in syngas production from biomass waste and the solution it was provided for each gasifier type.

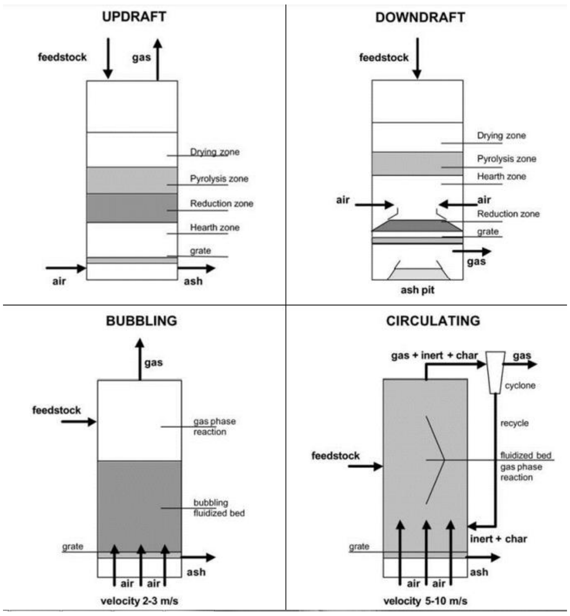

Fig. 1. Four gasifier operation principles, fixed bed (updraft, down draft) and Fluidized bed (circulation, bubbling) [14]

2.1. Fixed-bed gasifier

As for fixed-bed (updraft, downdraft) gasifier the challenge in maintaining the desired temperature and mixture composition in the process area which can lead to inconsistency in the products.

2.1.1. Updraft type

The particle size range of feedstocks for updraft type range between 2 to 50 mm under pressure range 0.15 to 2.45 MPa, with a residence time 15 to 30 min. The long residency time result in low efficiency and throughput and high tar content, thus it is not recommended for internal combustion engines instead its more suitable for heat generation. In one of the studies which used wood chips for an 8.5 MWh updraft gasifier to produce syngas, and without modifying the normal operation conditions of the gasifier or the properties of the feedstock. It recommended the usage of updraft gasifier when the fuel moisture is 20% with particles that is larger than 6.3 mm, since it would achieve a higher syngas quality and lower tar concentration [17]. Another solution presented in another study where a comparison between an updraft and downdraft type gasifier was conducted to produce syngas out of municipality green waste. It showed that incorporating a circulating cyclone to updraft type yield a higher gas output by 10–15% to downdraft type which is normally have a higher yield and lower tar formation performance. This is mainly due to recirculating the syngas inside the reactor back to the combustion zone which lead to higher rate of thermal decomposition of volatile organic substance, thus reducing tar collection [18].

Another major advantage is the ability of the updraft to handle biomass with high inorganic content with high moisture which is mainly suitable for municipal waste feedstock [19].

2.1.2. Downdraft type

The second type of fixed bed gasifier is the downdraft, where the typical size of feedstock ranges between 1 to 30 cm with moisture content up to 30% and its mostly suitable for high volatile fuel for power generation. It usually suffers from high ash content when compared to the updraft type, but when its compared to updraft type its much suitable for combustion engines since 99.9% of the tar is been removed in the process [19]. In a study that utilized agricultural waste in Scotland using the typically used downdraft gasifier type in a combine gasification with CHP engines for power generation. It tackled the design constraints and optimization of downdraft gasifier to achieve better yield from the gasification process as well as reduction in tar formation. It was found that with a moisture content of less than 10% and an equivalence ratio (Φ) of 0.3–0.35 would yield a higher syngas output efficiency. The equivalence ratio also has favored gasification temperature thus leading to lower tar formation. According to the study the highest heating value was found for barely dust which is the main crop in Scotland and barely screening (6.4 MJ/Nm^3) with tar content circa 2%mole % of produced gas) [20].

2.2. Fluidized bed gasifiers

Fluidized bed gasification main advantage is maintaining the uniformity of temperature in the combustion zone.

2.2.1. Bubbling fluidize gasifier

It has many advantages since it can accept a wide range of particle sizes, Main advantage its high yield with low tar content produced from this type < 1–3 g/Nm^3 and low unconverted carbon, as well as yield a uniform syngas as it also achieves a uniform temperature distribution throughout the reactor between 700 and 1000°C by controlling the air/biomass ratio [19]. In a study that used a bench-scale fluidized bed reactor, and feedstock from biomass waste (switchgrass, pine residues) at operating temperature circa 780°C, equivalence ratio (Φ) = ~0.32. They investigated the effect of the be materials such as sand, Al_2O_3 and CaO on the overall yield of containment, and tar reduction. It was found that the usage of Al_2O_3or CaO has reduced tar production circa 5.8 to 6.5 gtar/kg dry biomass through thermal cracking and oxidation reactions [21].

2.2.2. Circulating fluidized bed gasifier

The gasifier operates at high pressure, this would be ideal for usage of the gas that is require to be compressed in the later stages, such as in applications for gas turbines. It has many advantages in term of the speed by which the reaction occurs, and provide products with high yield, low tar and unconverted carbon. Although there is some technical downfall on the gasifier due to the rapid production rate, which can also be limited by the fuel particles size that determine the speed of the flow and the stability of the production becomes a concern after long operating duration and the bed materials should have strong abrasive materials [22]. In a study that investigated the potential of using a combination of synthetic and mineral catalysts to achieve better syngas yield production and lowering tar was able to achieve promising results. The catalysts used in the gasifier is of an importance factor in increasing the reaction rate at low-temperature, and the conversion of tar into valuable syngas via thermal cracking, steam reforming, and dry reforming.

The synthetic catalysts give better results but the downfall its high cost, while minerals can achieve good results but it could not yield in satisfactory results. The feedstock used in that study was pine sawdust collected from wood treatment plant, feed to a circulating gasifier operating under 750°C to 950°C temperature with the gasification medium was air. At first the experiment compared the reduction percentage of tar by using non-active bed material (silica sand) to a Raw-olivine, the results show a 40.6% reduction using Olivine, and a far much better results were achieved when using synthetic catalysts Fe (5%) in combination with Olivine to reach 81.5% reduction in tar compared to raw-Olivine because of the existence of because of existence of Fe_2O_3, NiO and NiO-Mg [23].

2.2.3. Syngas composition and applications

Understanding the effect of each component in the syngas along with their physicochemical properties on the combustion process in internal combustion engine would facilitate the understanding of the application methods for syngas in the different types of combustion engines.

In the following sections each component role and effect on the combustion process and thus the expected impact on the efficiency of the engine will be tackled. In the next section the specific application of syngas in Compression Ignition (CI), Spark ignition (SI) and homogenous charged compression (HCCI) engines will be discussed.

3. The physicochemical properties of typical syngas

The laminar flame speed and flammability limits are two elements that favor syngas as secondary fuel for internal combustion engines over other fuels such as hydrogen, biogas, methane or fossil fuels. In the following section we shall tackle the main burning characteristics of syngas, better understand the behavior of each component of the syngas effect on the combustion process, and subsequent challenges that arise in modeling this behavior in numerically form that can be generalized.

3.1. The laminar flame velocity

The laminar flame speed is one of the most important properties of the combustion process specially when operating an engine at fuel-lean conditions. The higher values promote for stable operation at lean conditions, and in ultra-lean spark ignition engines when syngas used as secondary fuel [24]. The laminar flame speed serves as basis to turbulent combustion, also contain fundamental information on diffusivity, reactivity, and exothermicity. The propensity of a flame, flashback and blowoff are heavily impacted by the laminar flame speed among other important combustion characteristics such as flame spatial distribution [25].

The importance of laminar flame speed led to various methods in obtaining its measurements, such as constant volume combustion bomb, heat flux method, Bunsen burner and externally heated diverging channel method [26].

There have been multiple tests published in the past about the laminar flame speed of syngas but they only tackle the combustion mixture at stoichiometric or at rich conditions, which is not suitable for modern combustion engines which favor lean-mixture [25].

The same issue could be said about the pervious published works regarding the kinetic schemes. The reaction model predictions that give numerical predictions of laminar velocities was found to have a lot of discrepancy between the calculated and experimental data [27].

In more recent research that studied the demarcation of reaction effects on laminar burning velocities of diluted syngas–air mixtures. Results showed that using modified Davis mechanism with lower third-body efficiencies can predict accurately laminar burning velocities of mixtures with high dilution of CO_2 and N_2 mixture. As for FFCM-1 showed comparable results at all dilutions except for high dilution of CO_2 circa 70%.

The final outcome of this study showed among other results the effect of dilution of CO_2, N_2 on the burning velocities. Where dilution of CO_2 specially at higher temperatures where N_2 had much less impact on the burning velocity [28].

The pervious study [28] was mainly concerned about tackling the discrepancy of LFS for high temperature and pressure (HTP) applications for Syngas. In another study [29] that tackled the discrepancy in the LFS data provided by literature under Normal Temperature and Pressure (NTP).

The discrepancies from different group of studies were presented in Fig. 2 between the results obtained from the OPF method vs David et al. using CHEMKIN-PREMIX code chemical mechanism for predicting LFS. As it can be seen in the Fig. 2 the discrepancies are very large at very lean and very rich mixtures, and with the discrepancy about 8 percent between equivalence ration (Φ) 1 and 3.

The source of uncertainty has been investigated, and the effect of the initial conditions and equivalence ratio has been presented. The results showed that the mixture preparation had insignificant impact on the measure LFS, such as slight perturbation in equibalance ratio, temperature an pressure. It was concluded that the linear extrapolation is more sensitive to the flame radius range than nonlinear extrapolation, which can strengthen the impact of the flame radius range selected on the uncertainty, in particularly at the very lean or very rich mixtures. The study ended by declaring that there is still a lot effort needed to reduce the uncertainties in measuring LFS [29].

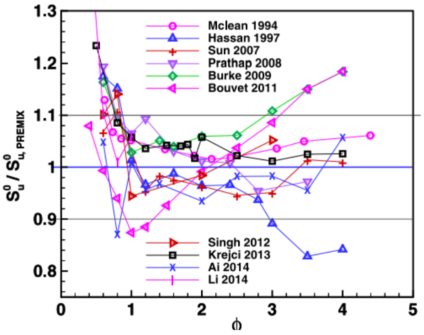

Fig. 2. Deviation of laminar speed measured by different studies in literature from the predicted laminar speed by simulation (PREMIX) based on the mechanism of David et al. for H_2/CO/air (H_2:CO = 50%:50%) at NTP [29]

3.2. Ignition delay time (IDT)

In an effort to solve the same issues of laminar flame velocity discrepancy between the measured and reaction model prediction calculations of IDTs. In addition to the emergence of advanced integrated systems such as ICCG as replacement to coal-fired conventional power plants. This promoted researches to reproduce the experiments using rapid compression machines and shock-tubes at higher temperature and pressures, whereas such data was only available at low temperature and pressured using mostly a shock-tube tube confined to a limitation up to 2.2 bar pressure and 2850 K temperature [30].

Following the effect of Pressure, Temperature and Equivalence ratio, CO, CH_4 on the Ignition Delay Time shall be discussed.

3.3. Pressure and syngas components effects on ignition delay

The influence of pressure on ignition delay was studied on multi-component syngas with and without ammonia having the following. The baseline mixture and the additional components were studied at 3 different pressures 1.6, 12.5, and 32 atm, at equivalence ratio (Φ) equal to 0.5 [31].

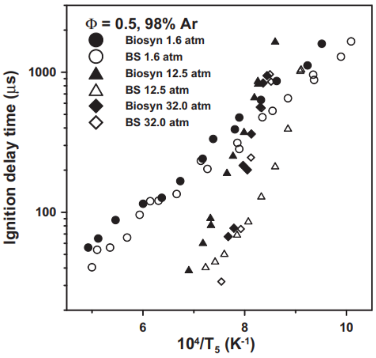

Fig. 3. Effect of the pressure on the ignition delay time [30]

In Fig. 3, a selected fuel composition was presented since the other compositions exhibited similar results, for example BS results where close to (Neat-H_2, BS-H_2O, BS-CO_2) and Biosyn to (BS-CH_4). The result shows an important effect of pressure on ignition delay values between 1.6, 12.5 and 32 atm [31].

At pressure 1.6 atm (Fig. 4) the following has been concluded that neat H_2 and BS (around 15% longer than neat H_2) exhibit similar ignition delay values, while the addition of H_2O to BS only slightly decreased ignition delay. As for temperature below 1550 K the results showed that ignition delay is further increased, compared to BS CH_4.

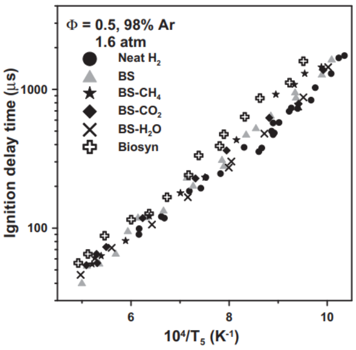

Fig. 4. Effect of the composition on the ignition delay time for a syngas with a H_2/CO ratio set to 1 and at a pressure around 1.6 atm [30]

3.4. Turbulent flame speed (TFS)

The inconsistency in the feedstock and different fuel composition of syngas by which it would replace traditional fuel. It mandates the investigation of all the combustion characteristics, such as TFS which is an important criterion in the combustion process. The high values of laminar flame speed due to high mass diffusivity of H_2 and subsequently lower Lewis number, required different operating conditions for engines to gives the intended performance and emissions of using syngas as alternative fuel. Such as improving the flammability limits, and enhancing the burning velocity and reducing the CO_2 emission [32].

Thus Turbulent flame speed is of high interest just as the LFS. In literature regarding the topic of measuring the TFS of syngas-air mixture focus on investigating the pressure, fuel composition due to concern of inconstancy in the feedstock supply, and obtaining (ST) coloration from experimental data at certain operating conditions and generalize them.

In a study that investigated the TFS of syngas at different compositions of hydrogen volumetric fractions (20%, 50% and 80%), at turbulence intensities of (0 to 3.54 m/s) and pressure (0.5 to 5 bar), and concluded with unified scaling of turbulent burning velocity. The experiment was conducted on spark ignition engine with constant volume, and to create the effect of turbulence inside a regular engine, fan-stirred turbulent combustion chamber was used.

At first the test was conducted under different turbulence intensities and initial pressures where the turbulent flame velocity where determined, secondly the turbulent flame velocity where compared under different hydrogen fraction in the syngas.

The results of the effect of pressure at constant turbulence intensity and vice versa is shown in Fig. 5.

The general understanding that the turbulent burning velocity increased as pressure and intensity increased. This relation is almost linear in case of intensity, but in reality (which is not covered as a range in this study) the turbulent velocity would reach a climax before it would actually start to decrease gradually due to local extinction. As seen in the Fig. 5b the growth becomes slower at higher pressures. This phenomenon is due to laminar flame thickness and Kolmogorov length scale which can be studied further in this reference [33]. In principle as the turbulence intensity and initial pressure increase, the flame surface wrinkles more intensely which leads increase in turbulence stretch and flame intrinsic. Thus, increasing the flame surface area.

The effect of hydrogen fraction in the syngas composition on turbulent flame speed is shown in Fig. 6, where the error bars represent the standard deviation of five loops.

The results show that the global turbulent velocity is more sensitive to hydrogen fraction with the increase in turbulence intensity as shown in (Fig. 6a). The same could be found in relation to the sensitivity of turbulent velocity to the turbulence intensity with the increase of hydrogen fraction. This could be explained due to the fact that the flamelets becomes more wrinkled with higher turbulence intensity, which in turn strengthened the diffusional-thermal instability [34]. As of result the turbulent burning velocity becomes sensitive to the hydrogen fraction in the syngas. The same could be said about the non-equal diffusion which is strengthened with the higher hydrogen fraction. Thus, the turbulent burning velocity will becomes sensitive to the flamelets wrinkling which is in turn dependent on the turbulence intensity.

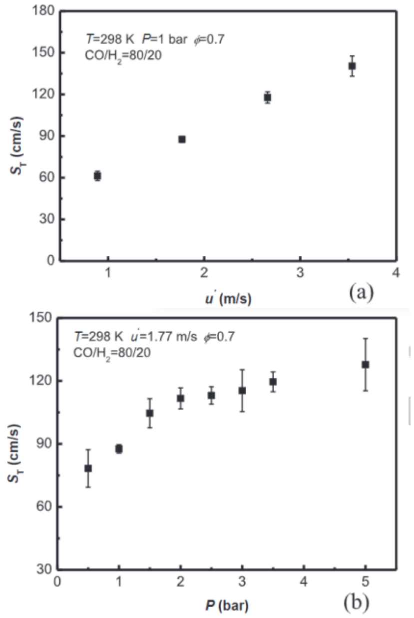

Fig. 5. Global turbulent burning velocity: (a) P = 1 bar under different u'; (b) u' = 1.77 m/s under different P [33]

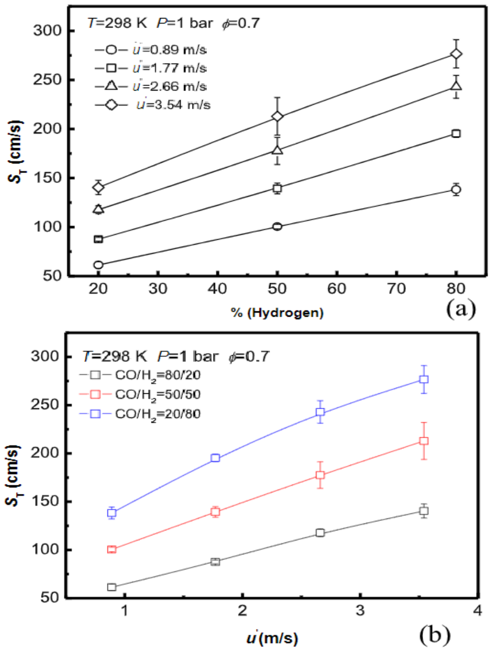

Fig. 6. Global turbulent burning velocity under different hydrogen fractions: (a) x-axis is hydrogen fraction; (b) x-axis is u' [33]

The obtained results match another research conducted to study the effect of higher hydrogen proportions of H_2/CO (5/95, 25/75, and 50/50 to 75/25) in syngas on turbulent flame speed, which indicated also an increase in OH radicals concentration. OH radical is a fundamental radical in the flame. Its concentration level can characterize the combustion intensity [35]. The setup used was a water-cooled McKenna burner, and mass flow controllers. In addition, their results showed that dilution of syngas with Nitrogen (varied from 0, 10%, and 30% to 50%) was found to give the reverse effect on turbulent burning speed.

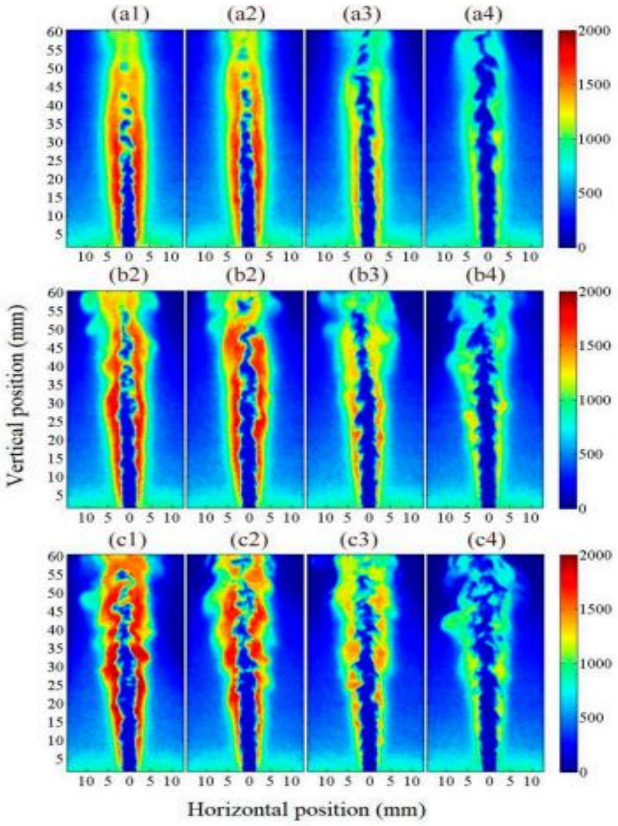

Fig. 7. OH distribution instantaneous image of syngas with volumetric ratio of 5% H_2–95%CO under different dilutions and Reynolds numbers: (a1–a4) Re = 6110; (b1–b4) Re = 10,690; (c1–c4) Re = 15,270. 1,2,3, and 4 indicate nitrogen dilution volumetric proportions of 0%, 10%, 30%, and 50%, respectively [36]

A unified scaling was conducted through dimensionless parameters to the turbulent burning velocity in order to extract general correlation of (ST) from experimental data.

The laminar flame and turbulence characteristics are two main elements that defines the turbulent burning velocity and thus it must be included in the unified scaling. The kinematic viscosity which is a dimensionless parameter in the turbulent Reynold number equation (Re = VDρ/μ) was used to reflect turbulence characteristics. Along with the ratio normalization of turbulent over laminar flame speed as show in Fig. 8, which was correlated with turbulent Reynold number ratio, suggesting that turbulent Reynolds number is a suitable to correlate turbulent burning velocity.

In quantitative level, the power exponent which 0.46 as show in Fig. 8, was found to be close to the experimental result 0.53 done by Shy et al. [37] and another theoretical result 0.5 of Chaudhuri et al. [38]. This indicated the validity of the unified scaling method regardless of initial pressures and type of fuels, so for the different turbulence intensities. The correlation obtained gave such satisfactory results due to the fact that most experimental results are at 20% hydrogen fraction and Lewis number around unity.

In another study they utilized the results obtained in the current study to verify their modified correlation for butanol/air flames $S_T \sim Da^{0.49}\ Le^{-0.35}$. With the difference between their correlation and the current study to having the Lewis number included in the equation [39].

The unified scaling method which includes Lewis number other than unity could be represented as follows with ST /SL ~ $Re_T^{0.36}\ Le^{-0.36}$, where the value of 0.36 close to 0.46 suggested by the current study. Additionally it was suggested that Da modified correlation (Damkohler number correlation) ST ~ $Da^{0.49}\ Le^{-0.35}$ is not only applicable to butanol/air flames, but also for syngas/air flames of different molecular transport effects as show in the Fig. 9.

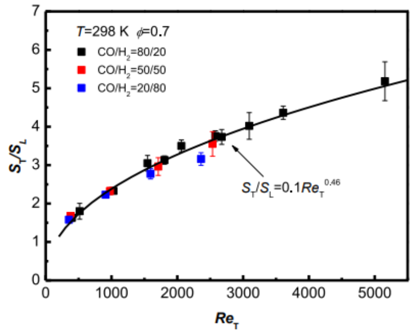

Fig. 8. A unified scaling of global turbulent burning [33]

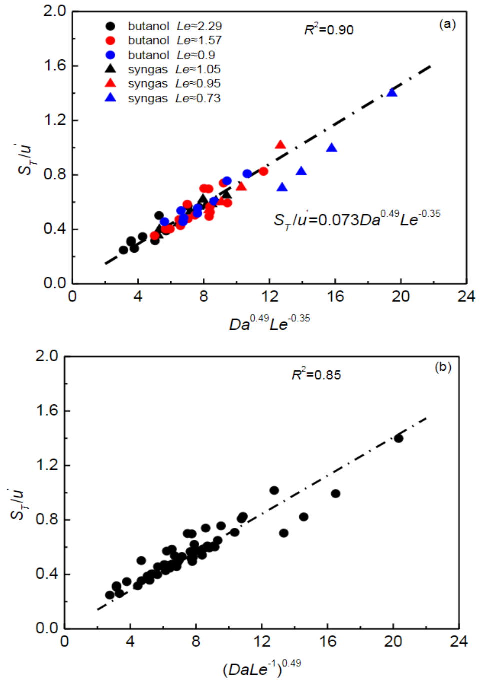

Fig. 9. Validation of modified correlation: (a) $Da^{0.49}Le^{-0.35}$, (b) $(Da\ Le^{-1})^{0.4}$ [39]

4. Syngas in internal combustion engine

Syngas has many applications in stationery and transport energy sector. It has been used a primary or secondary fuel depend on the type of engine, its operating conditions, performance requirements, and the phychemical properties of syngas. An important aspect for example is the autoignition in compression ignition engines (CI), which is difficult to achieve with syngas. Thus, diesel fuel is used as secondary fuel to help ignite the syngas-air mixture. The challenge then is to replace the highest percentage of fuel mixture with syngas, where literature providing wide range of solutions from 25% up to 90%. The necessity is to reach a better understanding of the behavior of syngas in combustion engines based on the many criteria that define those limitations. Among many applications we shall discuss about the usage of syngas in Compression Ignition engines (CI), Spark Ignition engines (SI), Homogenous compression engines (HCCI) and advanced dual engines called reactivity-controlled compression ignition (RCCI).

4.1. Spark ignition engines

The research on spark ignition engines utilizing syngas as alternative to gasoline mainly on the aspect of fuel consumption and emissions. Spark ignition engines operating with fossil fuel at lean or even extremely lean condition has been the focus of researchers, with main goal is to achieve higher thermal efficiency due to lesser heat losses a pumping energy requirements, as well as lowering NO_x with lesser combustion temperatures [40]. This trend continued with the current experimental which utilizing syngas as an alternative fuel, where the syngas serves as an extender to the lean limits of SI engine operation. This is mainly achievable by direct injection strategies and the dilution of intake charge. The improving of the engine performance through implementing the typical strategies such as boosting, utilizing EGR, and engine downsizing is under investigating for the syngas application in SI engines.

The usage of syngas in spark ignition engines can vary depend on the engine type. For instance, the syngas applications on direct injection SI, carbureted and port fuel injection, and modified CI engines into SI engines. Also, whether the syngas would be used as primary, dual or as secondary fuel, but more importantly the applicability of the syngas usage in term of its advantages and disadvantages.

Many considerations such as combustion process, the typical engine operating range, and the LHV of syngas which is lower than gasoline, causes droppage in engine performance. Therefore, it has led to favoring the usage of 100% syngas as primary fuel for portal port fuel injection and carburetor SI engines in power generation rather than for vehicular applications. Since the operating point of fixed engines are limited, thus it can be optimized and the possibility of engine modification is more suitable.

This has been demonstrated in a study that replaced gasoline with syngas for a 650 W Yamaha 950 generator set. The syngas was derived from wood pellets through gasification which had lower heating value of 4.5 MJ/kg. The modification was done on the engine included the lubrication system, the air and fuel flow control, and the ignition timing. The Ignition timing had to be advanced by 13 degree to compensate, as we explained in pervious section, due to the high laminar velocity of syngas. Whereas the 45% decrease in power output compared to gasoline of 360 W [41].

Despite the negative impact on engine performance, utilizing syngas in Spark Ignition engines has significant impact on reduction of emissions [42]. A study done using a laboratory scale gasifier and portable gasoline generator of 8.5 compression ratio and 2.8 kW. Their emission results showed consistency with another study done on generator running at 740 Watt [43], with maximum power output of 1392 W. It is worth mentioning that there is scarcity in experimental work which compares generators running on gasoline vs syngas since the year 2010 onwards. Table 2 shows comparison between gasoline and syngas emission results. The CO emission was less by 20 times compared to gasoline, and reduced of NO_x emission by one-third. In totality the emission flow amount was about 25% less when operated on syngas.

Table 2. Gasoline and syngas emission comparison [42]

Fuel	O_2 in exhaust [%]	CO [mg/m^3] @13% O_2	NO [mg/m^3]@ 13% O_2	NO_x [mg/m^3 @13% O_2	SO_2 [mg/m^3 @13% O_2
Gasoline	8.93	24,700	45.4	69.7	50
Syngas	8.5	14,000	22.8	35	n.d.
Syngas	8.8	3100	24	38	n.d.
Syngas	9.12	1250 I	21.0	32	n.d.
Syngas	10.1	1120	16.6	25.6	n.d.
Syngas	10.8	1700	15.9	24.6	n.d.
Syngas	11.4	4000	16.8	26	n.d.

4.2 Syngas for dual-fuel CI engines

Due to high self-ignition temperature of syngas, typically about 500°C [44], syngas cannot be ignited by compression ignition diesel engines, combined with the the low reactivity of syngas-air mixture in CI engines. Thus the solution is typically dual fueling method is used, where diesel is injected as a pilot fuel to initiate the ignition while syngas injected into the induction system.

The dual fueling where a premixed fuel and piolet fuel is injected is gaining moment in the research area due to the ever-strict emission regulation for diesel engines. Literature shows that utilizing syngas in dual system is to certain degree beneficial as the other alternatives in term of performance and emission such as compressed natural gas and liquefied petroleum gas, with the advantage over them being a renewable energy.

In term of performance, its been reported that there is a decrease in power output due to lower volumetric efficiency of syngas [45]. As for emission CO and HC reduction was mainly observed under medium load conditions, but in general there is an increase in emissions including soot and NO_x. Other studied resulted in concluding that the incomplete combustion and excessively high Ringing Intensity (RI) are the major challenges of RCCI engines with lean premixed syngas [46].

Many strategies are being developed to reduced emission and enhance engine performance, one of which the Reactivity Controlled Compression Ignitions, where an early pilot injection during compression cycle is introduced.

In a study that tested syngas-diesel fueled RCCI engine was numerically investigated using KIVA-3V code, which was validated with experimental work [47]. The influence of syngas composition on RCCI combustion were investigated. Eight typical syngas compositions at Initial temperature valve closing and 360 K and syngas premixed ratio 60%. It was found that the H_2 from 50% in syngas 4 to 75%

in syngas 8 as show in Fig. 10 inhibits the autoignition of the mixture due to the active OH radicals being consumed which is required by the diesel low-temperature oxidation. Therefore, it leads to a retarded initiation of combustion shown in the heat release graph, Fig. 10.

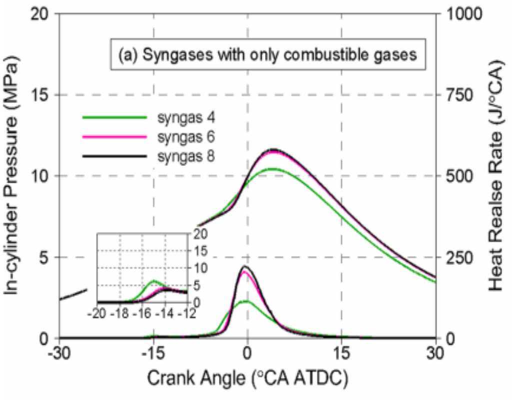

Fig. 10. In cylinder pressure and heat release graphs for pure H_2 and CO syngas. Syngas 4 (50/50), Syngas 6 (66.6/33.3), Syngas8 (75/25) [47]

The increase of H_2 lead to a decrease in combustion duration and higher thermal heat release rate which in turn lead to an increase in the combustion efficiency. Another syngas compositions were tested and it was found that the impurities for example CH_4 which transform OH to H_2O_2 can lead to a further increase in reduction of OH radicals which leads to lesser combustion efficiency. Soot reduction was also observed with the increase in syngas where the soot precursors H_2 and CO are mainly responsible for the soot reduction as show in Fig. 11.

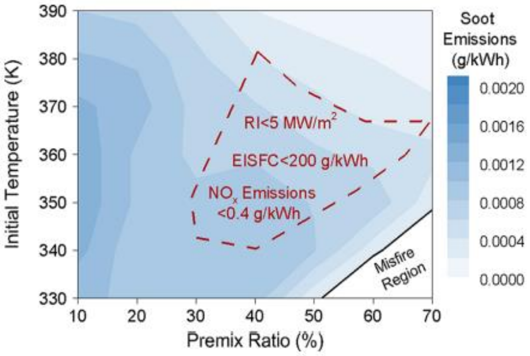

Fig. 11. Soot distributions under different initial temperatures [47]

The study concluded with suggesting an optimal syngas premixed ratio of 60% and H_2 volume fraction of 75% for best RCCI engine performance and lower emissions [47]. Similar results were obtained by another study where the H_2 optimal ratio range given was between 60–80% [46].

4.3 Syngas for HCCI engines

In the previous section syngas for spark ignition engines, we have mentioned that the usage of syngas for power generation is more suitable than vehicular application due the limitation syngas imposes on the operation of SI engines. Still syngas causes reduction in power by almost up to 40%.

Another major issue is the knock, which makes HCCI engine favorable as a solution for knock for syngas as fuel alternative in power generation applications.

For syngas to operate in SI engines it requires cooling to avoid knock, which leads to condensation of tar impurities that clog up critical process components. The tar removal procedure is costly and can make the usage of syngas economically unfeasible. HCCI which requires normally higher intake temperatures could be a solution to this critical issue in normal spark ignition engines. Thus the biomass syngas can leave the gasifier without having to go through cooling process to the HCCI power generator [48].

The knock limitation of syngas is mainly the topic that is been researched to identify the maximum compression ratio of HCCI engine, where the higher the compression ratio the better is the engine performance. According to the literature, for HCCI engines the low volumetric efficiency due to the addition of gas in the premixed charge, and the trade off between NO_x and CO remains an unsolved issues needed to be researched.

In a study done on an 435 cc mono-cylinder HCCI 12 compression ratio engine, tolerant to tar impurities above the tar dew point, they tested the sensitivity of HCCI to the ratio variation of H_2:CO from 30:70 to 55:45%.

Moisture up to 12% by volume, and tars (from 3 to 17 g/Nm^3) at the intake temperatures of around 250°C. The 250°C for the intake temperature experiment was chosen due to the fact that it the dew point of class 5 tar at a concentration of about 1 g/Nm^3, where there is mainly 6 classes of tar been identified, and class 5 dominating the tar dew point [48].

The results of the CO emission is shown in (Fig. 12b). Where the CA 10–90 represent combustion duration defined as the difference between the CA90 and the CA10, represented as the heat release duration. Since there is not any significant amount of hydrocarbon to contribute for the emission of CO, its considered that the CO emission is directly correlated with the unburned CO.

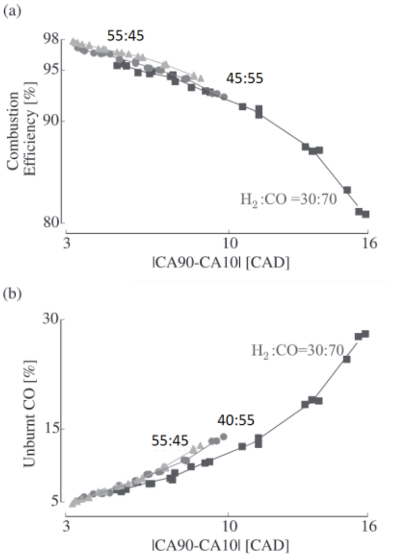

Fig. 12. Combustion efficiency and unburnt portion of CO measured in the emissions as a function of the combustion duration CA90–CA10 for various H_2:CO mixture ratios [48]

The similarity in the shape of the curve of the engine efficiency and CO is due to the slowing down effect on the combustion of the CO component.

It was also reported an increase in the NO_x emission as the combustion duration decrease, due an increase of the combustion temperature. The combustion temperatures in HCCI are still less when it's compared to SI and CI engines, thus NO_x emissions results are better for HCCI. It was also observed that the H_2:CO ratio did not have any significant effect on the NO_x emissions.

Besides the NO_x, CO trade-off issue in HCCI engines run on syngas, the volumetric efficiency issue has been investigated. The low heating value (LHV) of syngas along with high inlet temperature caused a significant reduction in the volumetric efficiency of the engine, thus low indicated mean effective pressure.

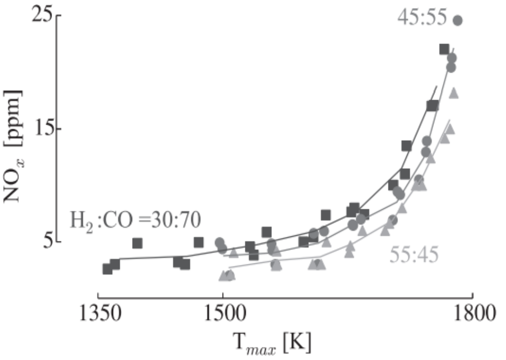

Fig. 13. Experimental NO_x measurements as a function of peak cycle temperature [48]

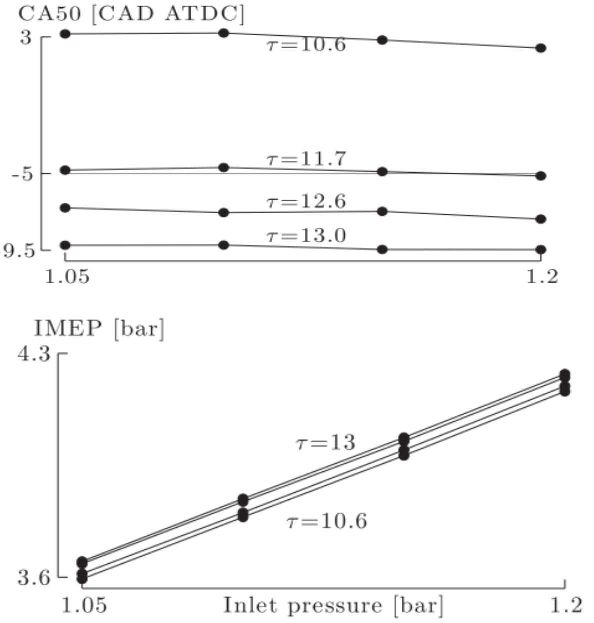

Fig. 14. Inlet pressure effect at different compression ratios on IMEP and CA50 [48]

For this purpose, researchers investigated the effect of pressure inlet effect. Satisfactory results were obtained which indicates that the workout of the engines could be controlled by adjusting the pressure inlet. Changing the compression ratio on the other hand showed a minimal impact on the IMEP, due to to high Maximum Pressure Rise Rate (MPRR) and improper phasing CA50. The best result for the whole range of pressure inlet where found to be at compression ratio 12, where the whole range of pressure inlet fulfilled the constraints they set for this study in term of CA50 (–5 and 10 CAD), engine knock MPRR (max 10 bar/CAD), and maximum cylinder pressure (100 bars) as it can be seen in Fig. 14.

Similarly, the temperature inlet had a significant impact on the (230, 250 and 270°C). The higher the temperature the earlier CA50 is achieved and the shorter the combustion duration. For instance, an increment by 20 degree in inlet temperature advanced the CA50 by about 8 degrees, with an increase in MPRR by 3.6 bar/CAD. Thus, it was concluded that As Inlet temperatures increases, the bad phasing decreases both the indicated efficiency and the indicated mean effective pressure (IMEP).

5. Summary and conclusion

This paper provided an in-depth review of the current syngas production processes and its applications, along with their utmost critical issues been tackled by the literature. Syngas as an alternative fuel has drawn recently increasing attention with the ever-stricter environmental regulations. The research area regarding syngas has mainly focused on the possible ways of achieving high production yields while reducing tar during the gasification process instead of being processed at later stages. This is mainly due to higher costs that makes syngas economically and technically invalid. Besides, the inconsistency of the feedstock components plays a major role in the combustion process of syngas as fuel in combustion engines, thus creating a greater challenge in accurately anticipating the combustion behavior of syngas at different loads, equivalence ratios, and initial conditions. Thus it necessitates to study each components and its effect on the combustion process. Based on the learned behavior of syngas during the combustion process, and the possible applications was discussed. The most important conclusions will be summarized as follows:

The main four types of gasification process as the mostly used tools to produce syngas from waste biomass feedstock has shown many advantages and disadvantages alike. Thus, it been recommended different applications to each type based on many criteria and their subsequent possible issues they could create in the engines. Multiple possible way was suggested to tackle those issues to reduce for instance their tar production and increases their yield production rate. For instance, incorporating a circulating cyclone to updraft type shown to yield a higher gas output by 10–15%, which is due to its feedstock long residency time, result in low efficiency and throughput and high tar content. Thus, it was not recommended for internal combustion engines, instead it was found to be more suitable for heat generation engine applications. Whereas the downdraft gasifier being the favored method so far in term of tar production rate with 99.9% being removed, which makes it suitable for engine combustion engines, mainly for high volatile fuel for power generation applications.

Unlike circulation fluidized bed, budding type is capable to acquire larger feedstock particle size, whereas for circulation gasifier type the particles size becomes a hindering criterion since larger sizes lowers and cause unstable production rate. Thus, the advantage of the bubbling gasifier bed is the uniformity in syngas production, where it maintains a uniform temperature distribution throughout the reactor between 700 and 1000°C by controlling the air/biomass ratio.

The physicochemical properties of a syngas in terms of laminar flame, turbulence flame speed, ignition delay, and knock limitation are considered to be the most important aspects has been researched in the effort to better understand the combustion behavior of syngas in combustion engines. The current literatures all agree that the discrepancy between the numerical and experimental data results need more investigation to tackle the reasons behind it, in an effort to speed up the study of syngas as an alternative fuel for combustion engines. In that regard the effect of highly diluted syngas (CO_2 and N_2) on the laminar flame speed was investigated. Results showed that using modified Davis mechanism can predict with high accuracy the LFS for application which requires high temperature and pressures such as for advanced technologies IGCC. Whilst FFCM-1 method resulted in comparable results except for high dilution of CO_2 circa 70%. In case of low temperature and pressures application, an investigation was done to better under the reasons behind the discrepancies between the results presented in the literature which used Davis mechanism and the measurements obtained using OPT method. The source of discrepancies was found to be mainly at very lean and very rich mixtures, with about up to 45% percent difference. It was due to the ignition which has strong impact on the uncertainty, as well as the extrapolation method used to study the LFS at early stage of spherical flame propagation, where the nonlinear method were found more sensitive to the linear extrapolation method.

The different production processes of syngas that constitute the product components and the physicochemical properties defines the applicability of syngas in different combustion engine type. Compression ignition engines self-ignition requirements cannot be met for syngas at about 500°C, thus it usually used in dual mode where the challenge to increase the ratio of syngas as the primary fuel. Such applications have been investigate and literature is giving a wide range of solutions from 25% up to 90%. The higher the percentage the lower the volumetric efficiency, thus the lower power out can be achieved. Besides the reduction of emission is limited to CO and HC at particularly medium loads while there is generally an increase in soot and NO_x. To overcome these issues advanced technologies such as RCCI engines can be more suitable for syngas application, although their main challenges when operating with syngas is the high ringing intensity and incomplete combustion, which requires further investigation for a complete adaptivity. For RCCI engines multiple studied suggested that the optimal syngas premixed ratio of 60% and H_2 volume fraction of 75% for best RCCI engine performance and lower emissions [47]. In spark ignition engines (SI) the syngas is mainly been investigated as an extender to the lean limits, since the advanced engine technologies already been designed to operate on very lean mixtures. Thus, the typical strategies such as boosting, utilizing EGR, and engine downsizing is under investigating for the syngas application in SI engine, taking into consideration the lower LHV of syngas compared to gasoline which leads to lower of engine performance. Syngas in that regard were mostly found to be useful in power generation rather than vehicular applications since the engine calibration can be easily modified to fit the limited operation points in stationary engine applications, with an advantage of reducing CO and NO_x emissions by up to 25%. Another main concern in spark ignition engines is knock. As a solution HCCI engines serves as viable alternative to regular SI engines when operating on syngas fuel. This in turns solves the tar major issue in syngas usage. Unlike SI engines, HCCI operates at higher intake temperatures which avoid the necessity to cool syngas which causes tar formation. As of result the combustion temperatures in HCCI could increase affecting the NO_x emissions but when its compared to SI and CI engines its of a lower NO_x emission values. The main challenges been investigated in such types of engines is the effect of initial pressure and temperature on the combustion duration to achieve the lowest emission with highest engine output power.

Syngas has a promising protentional to be usage as alternative to traditional fossil fuels when its physicochemical properties can be fully studied and numerical models are established. This would help facilitate the speed up of the investigation of syngas behavior in different engine applications to set the recommended percent usage and initial conditions. It can be concluded that:

- Downdraft gasification is the most preferable type currently been used to produce almost tar free syngas.
- Other gasification types showing an improved and promising tar and yield production rates with newly proposed solutions, yet it requires further investigation and research.
- The physicochemical properties of syngas in term of turbulent, laminar flame speed, and ignition delay time is not fully yet comprehended. Which explains the significant gap and discrepancies between the numerical models and the experimental results.
- Although there has been a significant progress in establishing a reliable models that can speed up the research of syngas as alternative fuel.
- Syngas has wide range of application in ICE, although its limited due to its physicochemical properties such as self-ignition temperature, where it could only be used in dual fuel CI engines.
- The applicability of syngas in stationary engines were found to be more favorable than in vehicular engine application due to the limited operation ranges that can be modified and controlled.

Nomenclature

Al_2O_3	aluminium oxide
Ar	argon
BS	baseline syngas
CA	crank angle
CH_4	methane
CI	compression ignition engines
CO	carbon monoxide
Da	Damkohler number correlation
EGR	exhaust gas recirculation
Fe	iron
FFCM	foundational fuel chemistry model
H_2	hydrogen
HCCI	homogenous charged compression
HTP	high temperature and pressure
ICE	internal combustion engines
IDT	ignition delay time
IGCC	integrated gasification combined cycle
IMEP	indicated mean effective pressure
Le	Lewis number
LFS	laminar flame speed
LHV	lower heating value
Mg	magnesium
MPRR	maximum pressure rise rate
NiO	nickel oxide
NTP	normal temperature and pressure
OPF	outwardly propagating spherical flame method
Re	rhenium
RCCI	reactivity-controlled compression ignition
SI	spark ignition
Φ	equivalence ratio

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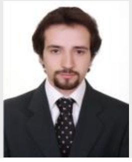

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