Chapter 2. Review of PG-fuelled IC Engine Operations

This section mentions the reviewed progress in the utilization of waste-based producer gas as a fuelling component for the IC engine application towards the scope of waste-to-thermal energy conversion. The domains covered in this section transactions with PG as a renewable source of energy, PG utilization in IC engines, advantages with the SI engine application, significance and previous works regarding optimization operations, advantages of the RSM-based optimization approach, scope for engine performance numerical modelling, and performance improvement through analysis of ignition timing optimization, better quality fuel-component blending, and miller cycle strategy adoption for enhancing engine performance with boosting the intake charge to gain better volumetric efficiency.

2.1. Producer Gas generation via Gasification

With a significant estimated increase in the net SS generation by next thirty years, the volumetric reduction of the SS-wastes becomes crucial [3, 4]. Thermal treatment has a potential to significantly reduce the sludge volume, maximum upto 90% [74], with the largest reduction being through water content reduction. As discussed earlier, gasification offers many advantages over pyrolysis and incineration-based thermochemical methods in terms of CO emissions and net-energy extraction potential [28]. Concerning thermal treatments, the incineration method destroys pathogenic microorganisms and hazardous organics by complete oxidation [75]. However, the incineration produces hazardous chemicals including dioxins, N_2O, NO_x, HCl, SO_2, HF, and furans. Besides, the ash residuals could also be concentrated with heavy metals [11]. Pertaining to such downsides and with sustainability-based perspective, the thermal sewage sludge management systems have been increasingly based on pyrolysis and gasification processes, with a significant focus on energy recovery and increasing heating value [11]. These strategies involve thermally treating the dry sludge pellets at temperatures ranging from 300-500°C (often around 450°C) and resulting in the production of biogas as well as biochar which are energy-rich useful components [76]. The incineration is generally implemented in the scope of industrial farming-based applications like recycling cattle waste feed [77]. Bridle et al.[78] also described that this treatment method also degrades feed material into oil, char, Non-condensed gas (NCG), and Reaction water (RW). These products could be unwanted and hazardous as well. However, through the confined oxidation environment availed in the gasification, the sulfur, nitrogen, and chloride contents produce hydrogen sulphide (H_2S), ammonia (NH_3), and hydrogen chloride (HCl) in the post-gasification residual matter. Thus preventing the generation of dioxins such as sulfur dioxide (SO_2) and nitrogen oxides (NO_X), while also making gas-cleaning installations smaller and less costly than traditional combustion methods [29]. Besides this, the gasification strategy is also significantly more energy-efficient than incineration [79]. Thus, this technique offers significant waste-to-energy reusing potential.

Concerning energy-extraction, gaseous biofuels like Producer gas (PG) offer advantages over solid and liquid biofuels due to their superior combustion efficiency and higher heat release rate [80]. Additionally, gaseous fuels are more manageable and allow easy control and adjustment of power output. Thus, they are preferred for various heat and power applications over solid and liquid fuels [80]. As discussed earlier, the MSW and sewage sludge could be converted through various technologies, including direct combustion, thermochemical, biochemical, and agrochemical processes [81]. Among these, the thermochemical conversion processes, particularly pyrolysis and gasification routes, have gained significant interest due to their ability to produce easy-to-handle gaseous, liquid, and charcoal fuel components [82, 83]. Therefore, gasification is favoured over the pyrolysis process as it offers a greater biomass conversion efficiency [82]. Gasification technology is a thermochemical partial oxidation process, has a substantial potential to convert wastes or carbonaceous material into combustible gases (i.e., producer gas or syngas), that can then be converted to engine-based electricity and biochar, which has a high carbon sequestration potential [48, 84]. In general, the gasification process deals with self-sustaining energy input chemical reactions in the presence of oxidizing agents (i.e., air, steam, N_2, CO_2, and O_2). It comprises different thermal zones i.e. drying (0–250 ◦C), pyrolysis (250–550 ◦C), oxidation (800–1000 ^{0}C), and reduction (800–600 ^{0}C) [85, 86]. Gasification involves partial oxidation of raw biomass (below stoichiometric values, like 0.2 to 0.4 [87]) into gaseous alternative fuel by utilizing gasification agents like oxygen, air, steam, or their mixtures[88-92]. Different biomasses provide differing qualities of Producer gas (PG). The gasification technique is suitable for cheaper raw materials like residual sewage sludge, possessing a net solid content between 70-95%. Sewage sludge feedstock might be utilized for gasification procedures after drying the secondary sludge following biological-chemical wastewater treatments [29]. A.H. Alaedini et al.[28] also mentioned that residual digestate after digestion is correspondingly also fit for further energy extraction via thermochemical processes like gasification, to form the producer gas. As discussed earlier, gasification offers many advantages over pyrolysis and incineration-based thermochemical methods in terms of CO emissions and net-energy extraction potential [28].

After the STP-feed is processed through low-load activated sludge for reducing phosphate and nitrogen content from wastewater [29], mechanical drying could be performed with the residue available prior to the anaerobic digestion and dehydration. This results in granular structure, which is appropriate as the gasification feed [29, 93]. Figure 1.2.1-A,C depicted this sample for the gasification. Gasification residue is a relatively concentrated source of minerals and organic elements, which renders it important as fertilizers. It is a viable alternative to natural phosphorus ore as described by Gorazda et al., 2017) [94].

An additional aspect of sewage sludge management and utilization of the downdraft gasification technology is to produce hydrogen from sewage sludge. This is a unique and potentially useful technology since hydrogen synthesis is quite comparable to fossil fuel production [95]. According to Midilli et al. ([96], 2002), the producer gas yields around 10%-11% hydrogen, which can further be used in fuel cells after separation. Moreover, according to Angerbauer et al.[97], *Lipomyces starkeyi* -yeast variety has further shown the potential of producing biodiesel from sewage sludge. According to Ahmad et al. ([98]. 2016), sewage sludge residue post the gasification may also be utilized as a substitute for limestone, sand, and other raw materials in cement manufacturing, and lightweight aggregates, bricks, and ceramics. Such applications are limited only by the mechanical characteristics of the final product and could be benefitted by simple reinforcing strategies [99, 100].

2.2. Fuelling IC engines with Producer gas

As per the reports in ref.-[48, 82], more than 80% of the global energy demand, including high-quality heat, propulsion work, and electricity, is generated from combustion-driven processes utilizing fossil fuels. Moreover, the utilization of fossil fuels through internal combustion engine applications produced a significant impact on global warming and environmental pollution. To urgently comply with the recent global emission norms, the engine technology should incorporate fuels that minimize greenhouse gas emissions during the entire energy production and consumption processes[48]. Implementation of renewable energy sources like biofuels or Producer Gas in dual fuel (DF) mode internal combustion (IC) engines, is an appealing technology.

So far as the application part is concerned, the Producer gas or syn-gas can fulfil the demand for small-scale off-grid power generation and development of rural area economy. However, the performance characteristic of Internal combustion (IC) engines highly depends on fuel composition and operating parameters. This is because, the fuel interchangeability with blending needs to be nearly identical in terms of combustion characteristics, efficiency, and flame speed [58]. Thus, the investigation of the fuel interchangeability in IC engine performance, efficiency, and emission is a critical topic. In this respect, recently several works have been performed and advanced in the area of combustion improvement, engine design, and operating variable management in order to enhance engine performance with low emission, cost, and PG-oriented tar tolerance improvement. For example utilization of biomass-based PG as surrogate fuel for SI engines [101], [102]; CI engines [103], [82]; homogeneous charge compression ignition (HCCI) engines [104], and variable compression ratio(VCR) engine[80].

All of these studies show that PG can be successfully used in an IC engine under certain conditions, as PG blends promote thermal efficiency increment and emissions decrement. However, these criteria vary with engine configuration and operational variable settings [48, 82]. One of the major disadvantages of PG utilization in IC engines is the derating of brake power [105, 106], which is due to the possession of low flame speed of PG (i.e. 20–30 cm/sec [107]) and low calorific value. Also, it has been stated that the use of producer gas to replace conventional fuel is limited to a certain extent because PG addition cannot concurrently ensure high performance and low emission [108]. According to the literature [39], [109], [110], such a power loss can be compensated by the strategy of blending PG with a fuel of greater calorific value and laminar flame speed. Mostly, the fuel that has a higher H/C atom ratio offers improved power, efficiency, and low emission (due to low C-content) [111, 112]. Szwaja et al. [49] experimented and reported that power increases when an SI engine is fuelled with a PG-Methane blend, with up to 60% PG blend with methane, thus being satisfactory for engine run. However, it is also found to be highly influenced by the producer gas-air relative equivalence ratio ($\lambda \approx 0.6$-1.6). Methane blend is one suitable candidate for blending with PG because it can be a renewable resource of fuel while possessing a high H/C ratio for reducing carbon emission, and has a high Octane number (>120) for antiknock at higher compression ratio application [111]. Of course, high CV, H/C, and flame speed characteristics of fuel can improve the engine performance under prescribed conditions, however without setting the engine operating conditions, enhanced performance of the engine cannot be ensured at different loads and speeds. Some significant operating settings in this regard are: engine Equivalence ratio (ER), compression ratio, spark/injection timing, Inlet valve closing (IVC) timing, a rise in intake pressure, engine geometry, etc [48, 82, 108]. On the other hand, optimization of operating variables is highly essential to opt for Government emission regulations with efficient engine performance. Moreover, there is a substantial engine performance trade-off in relation to the variable engine settings. For example: maximum engine efficiency is found in lean mixtures(<1.0 ER), whereas maximum power is found in slightly richer mixtures(>1.0) [82, 113], thus best efficiency and power cannot be held at same equivalence ratio. Regarding emission, NO emission maximizes at slightly lean condition, where maximum thermal efficiency lies, however this mixture has a tendency to lower CO formation [110]. Similarly, NO_X emissions are raised when the ignition timing is advanced and decreased when it is retarded. Moreover, the Maximum brake torque (MBT)-spark timing offers maximum power with higher level of NO emission, therefore slightly retarding of spark timing from MBT is preferred [114], but it reduces thermal efficiency [115]. The efficiency increases with increases in Compression ratio (CR), but it promotes NO_X formation too[116]. Regarding IVC time, extended Late inlet valve closing (LIVC) improves the indicated thermal efficiency while concurrently reducing trapped volume, thus reducing power; however NO formation decreases due to lower rise of temperature and pressure in the cylinder[117]. Thus, engine variables must be optimized while using renewable fuels in order to achieve the best response of balanced power, efficiency, and emission.

2.3. Preference for the SI engine

Considering IC engine application, Hyunwook Park [102] et al. suggested that the SI engine is technically a more viable option in comparison to CI and HCCI engines for electricity generation through syngas combustion. The application of PG to fuel Spark ignition (SI) engines has major advantages in terms of significant HC, NO_X, and smoke reductions as compared to conventional gasoline fuel. This is possibly attributed to the H_2–content in PG that enhances carbon-conversion efficiency and the low relative calorific value (CV) of PG, respectively [48, 118]. Additionally, the net carbon emission also decreases as PG has low H/C [119] and carbon content [48] relative to gasoline fuel.

It was reported that considering the hydrogen-enriched syn-gas, a spark-ignition (SI) engine can be operated with syngas alone when its combustion is controlled by varying the spark timings [120]. In addition, with only a few small modifications in SI engines, syngas can be used in gasoline and natural gas-fuelled engines[37]. Many instances of such application are: syn-gas with biogas fuelled pre-mixed spark ignition (SI) engine[121], syngas with methane blended-SI engine having high compression ratio (CR) of 14, Syngas composition with 30% H_2 for SI engine operation at a high CR of 17 and intake pressure of 0.16 MPa[102]. Besides, applications for waste heat recovery [122], and with Miller Cycle approaches in SI engine [123, 124] regarding the electric power generation have also been reviewed for successful operational confirmation. It is observed that the direct way of increasing indicated thermal efficiency is either by increasing the compression ratio or expansion ratio [125]. It is reported [126, 127] that at present, Atkinson/Miller cycle engines are being significantly preferred for hybrid electric vehicles, as they considerably benefit at partial load conditions [128]. The efficacy of engine performance is closely related to the quality of the PG as fuel, which includes its moisture content, calorific value (CV), volatility, and flame speed [48]. For instance, Raman and Ram[37] compared engine efficiency with PG and natural gas-fuelling agents and found that PG-fuelled engine deceased efficiency degraded by more than 12%, attributing to the lower flame speed and CV of the PG. Similarly, PG-fuelled experiments conducted by Singh.et.al [41] showed a 45.71% reduction in fuel-usage, 69.5% decrease in NO_x emissions, and a decline in BP and BTE concerning low PG CV and flame-spped[37, 38]. Similarly, Homdoung et al.[42] also found that the lower energy density in the air/fuel mix-operated DF engine decreases efficiency, torque, and power. Investigations [43-46] also confirm that torque and power decrease, attributing to lower energy density and volumetric efficiency in PG-operated DF engines. Low CV and flame speed also result in lower heat release and energy density [37, 38]. Low energy density is a prime factor for engine power derating[39] whereas low flame speed results in unstable combustion.

As producer gas has poorer fuel quality than petrol and natural gas, engine design adjustments are required to attain comparable optimal power. However, Spark Ignition (SI) engines require relatively finer modifications for running on PG[53]. Thus, to increase power and efficiency, a fuel blend with greater flame speed and calorific value is significant to improve SI engine performance.

2.4. Significant engine response characteristics

For achieving better-desired engine responses, inspection of the suitable engine responses is very helpful. Towards developing an enhanced comparative perspective, the selected responses are described in this section under the categories of: in-cylinder combustion-depicting responses; power-depicting responses; efficiency-depicting responses; fuel and energy conversion indicative parameters; and modellable emission responses. Brief discussions regarding these categories have been presented in the following paragraph.

2.4.1. Combustion effectiveness-depicting responses

For PG-operated SI engines, a low Combustion duration (CD) might signify unstable combustion. This is because the flame speed for PG is relatively slower compared to the other conventional fuels [49]. Moreover, a longer CD necessarily signifies more combustion completeness and subsequently increased heat and work output [129]. Investigations presented in ref- confirm this occurrence and state that with boosting the intake, the relative in-cylinder temperature, pressure, and turbulence also increase. And consequently, the energy density in the induced fuel-air charge enhances, and results in more stable and prolonged combustion [102]. With the increase in PIVC, a significant increase in PP could also be confirmed, which suitably justifies the previously mentioned phenomena of enhanced combustion stability. Intense PP limits the PIVC towards cylinder endurability constraints and thus, the PIVC of greater than 3 bars is generally not considered for evaluation. The Miller cycle effect also impacts the in-cylinder combustion characteristics significantly. For instance, delay in IVC, could gradually reduce CD as observed in the investigation of ref.-[128]. As LIVC increases, the trapped fuel-air charge inside the cylinder reduces. This subsequently reduces the charge available for combustion[128] and thus the CD declines. Moreover, increasing intake-boosting densifies the intake air-fuel charge. This simultaneously enhances combustion stability and shortens CA-durations for attaining the PP(CA-PP) [102, 130]. Thus, observing the CAPP response has also been partly considered for this investigation.

2.4.2. Power-depicting responses

The parameters of Indicated and Brake powers (BP, IP), and Indicative and Brake-mean effective pressure parameters (IMEP, BMEP) have been considered independently in the different results and discussion sections pertaining to the particular investigation approaches (in Chapter 4). Brake power (BP) signifies net power at the crankshaft[131] whereas IP is defined as the power developed at the piston head of the IC engine [39]. On the other hand, IMEP and BMEP represent represent engine power regardless of the engine size (displacement volume). The difference between the IMEP and the empirically obtained Total-motored friction mean effective pressure (TFMEP) gives the Brake mean-effective pressure (BMEP) [132]. Hence, they are vital parameters for comparing the varying-sized engines [110]. It is the ratio of indicated power to displacement volume [110]. An increase in all of these parameters is desired for enhanced engine performance.

2.4.3. Efficiency-depicting responses

The parameters of Indicated and Brake thermal efficiencies (ITE and BTE) are also considered in various investigation sections. ITE and BTE are the ratios of indicated and brake power outcomes, respectively to the calorific value of consumed fuel rate [133]. BTE is a vital performance metric to evaluate and compare the fuel-to-power conversion in an IC engine operation as well [80]. An increase in these parameters is preferred for enhancing the engine performance.

2.4.4. Fuel and energy conversion parameters

Under this category of responses, the Brake-specific fuel consumption (BSFC) and Brake-specific energy consumption (BSEC) were included in the involved investigation and have been discussed in the results section. Brake-specific fuel consumption (BSFC) signifies how effectively the rate of consumed fuel is converted into shaft power. It is the ratio of the fuel consumption rate to the obtained brake power [29]. On the other hand, BSEC is considered as this investigation utilizes inputs of blended fuel composition of two different gaseous fuel mixes, which possess different energy densities [134, 135]. BSEC theoretically represents the inverse of Brake-thermal efficiency (BTE) [135]. A decrease in both, BSFC and BSEC parameters is desired towards enhancing the engine performance.

2.4.5. Modellable emission responses

The modelled emission responses were that of CO, NO, and HC. They were modelled with the rate kinetic approach along with the model-specific approaches for each response. Possible incomplete combustion is more likely at increased SSPG blends, thereby attributing to more supply of lean mixture and increased CO-generation[49]. Increasing SSPG is found to decrease NO emission, attributed to the increased oxygen unavailability[136]. Therefore study of the tradeoff is significant towards fuelling SI engine with PG application.

2.5. Scope for Waste-to-energy conversion

On the other hand, concerning waste management and effective waste-to-energy conversion perspective Sewage sludge (SS) generation has been a global concern. SS is the main byproduct of wastewater treatment. Worldwide its quantity turns up to around 45 million tons of dry-SS per year from municipal wastewater treatment plants (as reported in 2017)[4, 137]. This needs to be handled carefully to safeguard the environment. On the other hand, it is anticipated that the world will face a severe energy problem in the coming decades due to the continual depletion of fossil fuels [138]. The typical dry basis calorific value of municipal solid sludge is around 11.1– 22.1 MJ/kg, which is comparable to the calorific value of low-grade coal and biomass[4, 7]. Also, it contains significant thermochemical properties, around 7.27% moisture, 50.3% volatile matter, 7.73 % fixed carbon, 34.70% ash (proximate analysis), and 29.89% C, 4.34% N_2, 4.61% H_2, 1.06% S and 25.40% O_2 (ultimate analysis) [139]. Chen et al., also for instance, found that SS possessed 11.38MJ/kg calorific value (HHV) while composing 49% volatile matter, 40.3% ash and 10.7% fixed-carbon (dry basis wt.%, proximate analysis), and about 28.4% C, 25.58% O, 5.29% H, 4.65% N with 2.66% S (dry basis wt. %, ultimate analysis) [8]. The concerned approaches for sludge treatments and disposal are neither environmentally friendly nor cost-effective[5]. Alternatively, SS is also detected as a potential renewable and sustainable biomass source for energy production [6]. Accordingly, if the SS could be efficiently converted into energy, the twin problems of SS management and the energy dilemma might be partially resolved. Literature [49] reports the composition of SS gasification-derived producer gas (SSPG) as 13% H_2, 16% CO, 3% CH_4, 15% CO_2, and 53% N_2 by volume, processing 4.5 MJ/Nm^3 Lower calorific value (or LHV). However, depending on operating factors like gasification agents (air, oxygen, steam, or their mixture), gasification equivalence ratio (0.16-0.3), temperature, residence duration, and catalyst use, the PG composition and calorific value vary [36].

2.6. Scope for SSPG and methane fuel blends

In order to utilize PG fuel, an internal combustion engine is one of the viable options for generating electric power via a Gasifier-engine-genset integration system. Moreover, the application of SS-PG also has greater potential in terms of energy production[7]. SSPG application also results significant decrease in HC and NO_X emissions, with marginal CO emission increase[49]. And, a potential major gain in engine performance (in-cylinder pressure and indicated power) is also identified[4, 49], thus leading to higher energy conversion potential[7]. Therefore, undertaking evaluations towards improving the engine performance and efficiency, the authors endorse switching from conventional fuel to SSPG blend especially for systems like engine genset. But, from direct application in SI engine, the misfirings become prominent and the power output also reduces along with HC, CO, and NO emissions [49]. Concerning PG utilization in powering Internal combustion (IC) engines, the flame speed of fuel plays a significant role in combustion and power production. PG possesses a lower flame speed (20–30 cm/sec) [107] compared to Methane (38 cm/sec) or Gasoline (37-43 cm/sec) [140]. Due to this low flame speed and CV, it was found to derate engine power [39, 43, 45, 141]. Thus, blending PG with greater CV fuel reportedly improves flame and engine performance[39, 109]. Szwaja et al. [49] conducted an investigation on the SI engine fuelled with SSPG and Methane blends, and reported that the peak pressure and engine power increase with an increase in methane fraction until around 40% methane blend with 60% PG. A rise in PG content is found to hamper satisfactory engine run. They also revealed, that along with SSPG blend fractions, the relative equivalence ratio ($\lambda \approx 0.6$-1.6) also significantly controls the power (maximum at 0.9-1 λ) and exhaust emission of the engine. Methane application is beneficial as it is a renewable form of energy and can be obtained from biogas. It has a greater H/C ratio that results in low CO_2 emission and has a high octane number(120-130), which enhances the possibility of achieving improved efficiency through greater compression ratio(CR) [50-52]. Therefore, authors opted SSPG blending with methane in different proportions for investigating and predicting the optimal engine performance strategy.

Moreover, Methane gas contains fewer carbon atoms than diesel, it produces less smoke when burned. Methane has no carbon-carbon bonds and has a high hydrogen-to-carbon ratio, resulting in lower shooting tendencies. Furthermore, the natural gas-air mixture in SI engines is typically very well mixed just prior to combustion. This is due to the long time it takes the two gases to travel and mix from the intake manifold to the combustion chamber[142]. In addition to the methane contribution, literature [26] shows, producer gas contains CO_2 which reduces NO_X emissions but too much CO_2 leads to poor engine efficiency. It was reported [113] that HC and CO emissions were reduced significantly when producer gas was used as fuel in the same gasoline engine. Shah et al. [143] found up to 96% CO reduction due to lower carbon content in producer gas while switching from gasoline to producer gas. Thus, methane with SSPG blend has a significant potential to reduce the emission, however, a decrease in brake power with PG fuelled could be compensated by either rising CR or blending with methane under optimized condition. Table 2.1 tabulates the thermophysical properties of the discussed relevant alternative fuelling agents.

Table 2.1: Comparative physiochemical properties of relevant fuels

Properties	Methane [140]	Producer gas [107]	**SS-based PG**	Gasoline [140]
Composition	CH_4	Wood Biomass[144] H_2 V%: 17-20 CO V%: 18-21 CH_4 V%: 1-3 CO_2 V%: 8-12 N_2 V%: 45-50	SS-PG [49] CO V%: 16 H_2 V%: 13 CH_4 V%: 3 N_2 V%: 53 CO_2 V%: 15	C_5-C_{12} [145]
Lower heating value (MJ/Nm^3)	32.97	3.5–6	4.5 [49]	44.79 (MJ/kg)
Density at 1 atm and 15 ^0C (kg/m^3)	0.67	1.05	1.05 [107]	720-775
Flame speed NTP (cm/s)	38.0	20–30	20–30 [107]	37-43
Stoichiometric A/F (kg of air/kg of fuel)	17.2 [146]	1.2	1.2 [107]	14.2-15.1 [145]
Flammability limit (vol.% in air) (lean- Rich)	5.3-15.0	7-21.6	7-21.6 [107]	1.2–6.0
Research Octane number (RON)	120 [146]	100-105	100 -105 [107]	90-100 [145],[147]
Motor Octane number				81–92
Auto ignition temperature (^0C)	813	625	625 [107]	~500–750
Adiabatic flame temperature in NTP air (K)	2224	1800 [148]	1800 [148]	~2470
Minimum ignition energy (mJ)	0.28	-	-	0.25

2.7. Scope for Propane and PG fuel blends

Considering above mentioned views, since propane is a high-CV fuel material, and is acquired mostly as a byproduct during the refining of crude oil[149], it could also partially substitute PG for running the IC engines in DF mode and avoid output-power derating. It is a light component fuel and is formed as distillation, cracking, and other such refinery process by-products [66, 149]. Propane has a high-octane rating and is thus a cleaner fuel for power generation at medium as well as high-rated engines. This makes it an admirable choice for fueling SI combustion engines[39]. Considering these attributes, authors estimate that blending propane with producer gas could also deliver enhanced engine performance to counter the power derating and efficiency loss. Furthermore, a greater concentration of hydrogen(H_2) in the grape-based PG[39] carries advantages in both enhanced flame propagation and combustion stabilization inside the combustion chamber of a dual-fuelled IC engine[48]. So far as the availability of grape biomass is concerned, India currently holds the 7th position in grape production, with its grapes finding substantial export in various other countries. Moreover, India exports grapes to nations within the European Union, the Middle East, and Asia. In 2020, the worldwide grapes market was also projected to acquire a growth rate of at least 7.1% from 2021 to 2026 [150]. With this wider production forecast, the production of producer gas (PG) from the gasification of grape-biomass wastes could also be viewed as a new opportunity for utilization in engines for decentralized electricity generation, especially in remote areas.

Moreover, the advancement of IT affects the ignition delay period, which controls the in-cylinder and temperature rise in the cylinder and subsequently power deliverance [151]. The cylinder temperature affects the NO emission, as it decreases with low cylinder temperature. Literature [152] shows that around 0.9 equivalence ratio (<1.0 ER) NO formation maximizes. On the other hand, a greater calorific value (CV) increases peak pressure, which improves power, however, it leads to an increase in NO emission due to temperature increment. It was found that the grape PG-Propane blend offers greater CV for BP enhancement [39]. Another approach for enhancing the performance of PG-based dual-fuelled IC engines is by increasing the operational compression ratio (CR). Higher CR increases combustion chamber temperature and pressure which certainly increases the combustion efficiency, attributing to greater in-cylinder temperature and pressure conditions [153]. Papagiannakis and Zannis [28] thermodynamically evaluated the performance of wood gas with increased CR and reported that the brake power and NO increased, but CO decreased slightly. But, in SI engines, increasing the CR makes the engine operation more prone to knocking [154]. It was also found that using pure propane as an SI engine fuel has a knocking tendency even greater than hydrogen, possibly pertaining to its lower auto-ignition temperature [48]. In contrast to this, keeping a low compression ratio and stoichiometric operation, the thermal efficiency in conventional SI combustion mode is very limited [66]. Hence, increasing CR becomes a significant criterion to be investigated for the SI engines when blending is considered. And, blending of PG with propane or methane could also be beneficial towards lowering the knocking tendency upon application as a fuelling agent.

On the other hand, PG from grape-kernel features a relatively higher concentration of Nitrogen (N_2) [39]. And, mixed with the air-fuel charge, the N_2-concentration further increases, which chiefly acts as a knock preventer[39]. These discussed interpretations are expected to enable the grape-PG blending to potentially feature greater engine efficiency with increased CR levels. Overall, richer hydrogen content enhances the flame speed and combustion stability with PG, whereas nitrogen enables operation with greater CR and thus, enhances the efficiency. However, inspecting the SI engine performance and emissions when fuelled with potential blends of N_2-rich grape-based PG and Propane of high CV in different blend proportions, equivalence ratios, and CR remains a potential research gap.

2.8. Performance improvement strategies

2.8.1. Miller Cycle, Intake boosting techniques

Miller cycle engines are being significantly preferred for hybrid electric vehicles, as they considerably benefit at partial load conditions [128]. The Miller cycle can be accomplished by closing the intake valves either early (EIVC) or late (LIVC), via variable valve timing (VVT) technology [155]. The Miller cycle has several advantages, including improved thermal efficiency, reduced gas exchange loss, and thus improved engine performance when partially loaded, good anti-knocking against higher load and CR, and reduced end-gas pressure and temperature elevation, which tends to reduce NO_X emission and the chances for spontaneous combustion to knocking [125, 128, 155, 156]. In contrast, the drawbacks of a Miller cycle-based engine include a loss of power due to a smaller amount of air/fuel charge entering when using LIVC or EIVC methods [128, 157]. This issue is challenging, as efficiency and power are in a trade-off nature when LIVC or EIVC are applied. Thus, it needs to be optimized. Although the engine power can be increased through supercharging or boosting the intake charge, additionally, it is essential to have the best possible coordination between the Miller cycle and supercharging [128]. Recently, the Miller cycle approach has been applied in high geometrical compression ratio (GCR) to enhance efficiency, and supercharging is applied for intake charge to improve power. Park et al. [102] conducted an experiment with 17CR and 0.16 bar intake pressure of SI engine and reported that high compression ratios and intake boosting considerably improve the engine power and efficiency. Zhao et al.[127] reported that LIVC is most suitable for GCR application, as it offers low power loss compared to EIVC, and also improves turbulence intensity at sparking for better combustion, whereas turbocharged with EGR SI engine offers better fuel economy. Y. Wang et al. [46] revealed that a 35^0 CA retard in an inlet valve close with a geometric compression ratio of 25.5 results in a 48% BTE. According to J. Liang et al. [117], 12 geometrical CR with LIVC Miller cycle reduces BSFC by 4.7% in contrast to the normal Otto cycle of 9.3 CR and also has a strong anti-knock performance, however, the EIVC has minimal BSFC reduction ability. It was also shown that BTE initially increases and then decreases corresponding to delays in IVC, however, at higher loads, the LIVC strategy offers better BTE than EIVC [123, 157]. Therefore, while using new fuel in an engine, asynchronous valve timing must be optimized to balance engine power, pollution, and efficiency. Despite being a well-established technology, there hasn't been much research on the PG-Methane-fueled energy converters, especially when LIVC with boosted intake component is taken into account.

2.8.2. Strategies for apt SOI

With LIVC-strategy implementation to improve engine performance, the spark timing or start of ignition (SOI) optimization also plays a significant role in maximizing power, Brake-mean effective pressure (BMEP), efficiency, and even controlling the exhaust emission. Retarded ignition timing reduces the chances of backfire, but much retarded ignition (SOI) tends to increase abnormal combustion possibilities[114]. Whereas with SOI advancing, cylinder pressure increases during the compression stroke and leads to an increase in the compression work as a negative work [158]. It is suggested that for the fuel with more fast-burning ability than gasoline, a slightly retarded (shifting toward TDC) ignition is preferred, as it reduces the negative work against the fast fuel burn and enables the rapid rise of pressure at the compression region [159]. SOI has to vary with equivalence ratio, compression ratio, and blending ratio. S.K. Hotta et al. [160] experimentally found the maximum brake torque condition(MBT) timings of the biogas-fueled SI engine of 45^0CA, 39^0CA, 33^0CA, 29^0CA, and 25^0CA BTDC for CR 10, CR 11, CR 12, CR 13 and CR 14 respectively. H. Park et al. [102] experimented on syngas fuelled-SI engine and found 20^0BTDC and 24^0BTDC -MBT spark timing for equivalence ratio 1.0 at CR15 and equivalence ratio 2.2 at CR 17.1 respectively. Specifically, in a PG-operated SI engine, Homdoung et al. [42] observed 23.5% BTE with 40^oBTDC- MBT spark timing at 1500 engine RPM. Similarly, when sewage sludge-based producer gas is used in the SI engine as fuel, it was observed that over-advancing of spark timing creates misfire, leading to difficulty in attaining maximum IMEP or MBT, therefore, methane blending was suggested as one of a desired remedy[49].

2.8.3. Blending PG with high-CV agents

As derating of brake power [105, 106], is due to the possession of low flame speed of PG (i.e. 20–30 cm/sec [107]) and low calorific value, towards ensuring high performance without compromising with low emissions[108], the strategy of blending PG with a fuel of greater calorific value and laminar flame speed could benefit. According to investigations in literature [39], [109], [110], the power derating compensation through the strategy of blending PG with a fuel of greater calorific value and laminar flame speed is also confirmed.

According to the reviewed discussion, dual-fueled (DF) engine has several challenges in terms of their efficiency-power-emissions trade-off. Therefore, it is eloquent to investigate the combustion characteristics of DF engines, and subsequently perform optimization of the engine design/operating settings for obtaining the best response of performance with minimal magnitude of emissions. However, experimental analysis and evaluations towards finding the best operational parameters would certainly become very labor and resource-intensive, while also being too uneconomical.

2.8.4. Modelling for simulating engine responses

Thus, it could be assessed that it is significant to study the performance characteristics of dual fuel mode (DFM) engines and subsequently optimize the generated result respective to performance enhancement and emissions reductions. Intending to assess the performance proofing before experimentation and saving substantial resources, cost, and time investment, an engine modelling and simulation tool could offer a more anticipated platform[54-57]. It enables parametric engine performance predictions particularly in the early phases of engine design [58]. Literature works present the available engine simulation methodologies as: zero/one-dimensional (0D/1D) [55, 59], multi-zone-capable three-dimensional (like, CFD), and quasi-dimensional modelling techniques [55, 60], and Computational Fluid Dynamics

(CFD) modelling [61, 62]. Table 2.2 presents a comparison among these widely applied modelling techniques, which adeptly simulate the SI engine performance predictions.

Table 2.2: Comparison among the modelling techniques

	1-D	**3-D**	**QDTM**
1.	This is a complete thermodynamic model, based on mass and energy conservation [60, 65].	Along with thermodynamic modelling, this model intercepts cylinder-flow field details[65], using the fluid-dynamics approach [60]	This method integrates the turbulent burning velocity model to develop performance and exhaust species concentrations [60, 65].
2.	It uses a predefined mass combustion rate through empirical means, like the Vibe (or Weibe) law [60, 65].	The mass combustion rate is modelled [60].	The mass combustion rate $(dm_p/d\theta)$ is modelled using turbulent burn velocity sub-models. [65].
3.	Requires calibration [59]	May not require model calibration[59].	Requires calibration respective to differing engine operative-points [59, 60].
4.	One-dimensional modelling applies Ordinary differential equations (ODEs) [60].	Multi-dimensional modelling needs to apply Partial differential equations (PDEs) to capture spacial flow parameters [60, 65]	The quasi-dimensional modelling approach is flexible in terms of the type of governing equations [59].
5.	Single zone modelling [55]	Multi-zone modelling capability [55]	
6.	Gas dynamics are unaccounted for as spatial flow distribution is not considered [55, 65].	By this approach, the intake and exhaust gas dynamics are accounted for in the unburned zone [55].	
	Applications		

1.	Generally applied to examine the engine's overall parametric performance[65].	It applies best at generating detailed studies for limited conditions or particular features (For instance, flow through valves, fuel injection, bulk in-cylinder flow and turbulence development), or model development to support theory[60].	It is suitable for time-saving-parametric studies along with optimization works [65].

The QD model circumvents the limitations of 0D and 1D models and thus is a more accurate simulation technique [54]. Besides this, the 3D-CFD simulation depends on the sizes of the computational mesh and requires higher computational resources. Therefore, the QD combustion modelling is substantially practiced to predict and investigate the SI turbulent combustion without penalizing the prediction accuracy [63]. In this regard, the novelty of this study is in analyzing different engine operating settings through simulation and subsequent optimization for attaining better performance with minimum emissions. Moreover, the **novelty** of this study is to enhance the SI engine performance and to reduce the emission through the parametric operating setting of ER, CR, ignition timing (IT) with various propane blending fraction (BF) with PG. But such novel techniques have not yet been studied cumulatively, particularly for the DF SI engine operating with grape-based PG with Propane mix.

For bridging up the above-mentioned research gaps, this investigation works with the QD model to simulate DF SI engine performance and emission when operating with varying intake compositions of dual-fuel blend proportions with PG. Several strategies are also applied towards improving the engine performance outcome as well as the emission reductions. The models are first validated from the referred experimental findings and subsequently, based on the validation accuracy, the QD model is applied with single operating setting variations for determining the DF SI engine performance and emissions responses. Further, it can be concluded from reviewed literature works (Table 2.3) that despite the rising attention on biomass and gasification-based alternate fuel sources for SI engines, very few publications report on the quasi-dimensional numerical modelling and on further integration of the optimization strategy for declaring the optimal settings which best enhance the engine performance and reduce emissions. Further, utilizing the PG blends as fuel composition for predicting engine performance responses through the FORTRAN-coded QDTM model and integrating the analysis operation by utilizing Response surface methodology (RSM) is an additional novelty to this literature. RSM is an amalgamation of mathematical and statistical techniques for arresting such extreme requirements of parametric optimization with multiple operating parameters[161, 162]. Literature shows[163] that the Design of experiment (DOE) accompanied by RSM has remarkable potential for optimizing an engine performance-emission trade-off. RSM can conclude a better response compared to the artificial neural network (ANN) approach for engine performance [164], and fuzzy logic expert system [165]. Moreover, RSM proved beneficial as it requires less computation than ANN, besides generating simple polynomial-based prediction models[166]. Therefore, QDTM-based simulation results which have trade-off patterns in the response performance concerning the operating variables, could be optimized with a higher coefficient of desirability using RSM. RSM is a synchronized form of statistics-based mathematical optimization tool that can simultaneously model and optimize multiple input parameters constrained to the minimum and maximum output response [167]. The influence of vital input parameters was confirmed through Pareto charts[168] and the consistency of the RSM-developed statistical-based polynomial regression model is confirmed through greater values of coefficient of determination(R^2) [131], followed by the confirmation run [169]. Finally, the highest composite desirability (D) result is claimed as the optimal result. The novelty of the present work lies in developing numerical modelling and subsequently optimizing the operating parameters of spark ignition engines fuelled by methane and SSPG blends corresponding to the best response of SI engine performance and exhaust emissions. RSM is centered around preeminent normal fittings of the outcomes' statistics through regression-based polynomial equations. These regression models further illustrate the response to predict the statistical data [39].

Table 2.3. Previous investigation vs. this study

Type of engine	Modelling Operation		Modelling technique	Optimization		Optimization technique	Fuel	Operating Parameter	Ref.
Previous Investigation									
SI engine	✓	×	Polynomial neural network	✓	×	Pareto	Gasoline	Engine speed, Valve timing	[72]
SI engine	✓	×	Zero-dimensional coherent flame model	×	✓	---	Ethanol blended gasoline	Spark advance, Air/fuel ratio, Blend fraction	[73]
CI engine	✓	×	ANN	✓	×	RSM	Diesel blended with Acetylene	Injection timing, Injection pressure, Volume flow rate, CR	[67]
CI engine	✓	×	ANN	✓	×	Genetic Algorithm	LPG blended with Diesel	Load, Injection timing, Blend fraction	[68]
SI engine	×	✓	---	✓	×	RSM	gasoline–ethanol-blends	Engine Speed, Blend fraction	[69]
SI engine	✓	×	Ansys	✓	×	Taguchi	Gasoline-Methanol blend	Engine load, Engine speed, Blend fraction	[70]
SI engine	✓	×	QDTM	✓	×	RSM	Peach- PG with Propane blend	Blend fraction, ER and SOI	[103]
Present study									
SI engine	✓	×	Quasi-dimensional Thermodynamic modelling	✓	×	RSM	Grape- PG with Propane blend	Blend fraction, ER, CR and Ignition timing	

Note: '✓' represents included and '×' represents not included in the referred investigations

Thus, considering the above literature survey and subsequent research gap, this study aims to promote grape-based PG fuel generation through gasification by an assurance of simulated results of engine performance and emission assessment. Accordingly, the present study includes the following main objectives:

- To study the compatibility of dual fuel mode engine operation using QDTM-simulation approach to assist better engine operating prediction.
- To interpret the variation of engine performance and emission responses with regard to the variations in the four decision/input parameters.
- To demonstrate the specific response sensitivities towards various factor parameters through ANOVA.
- Determining the optimum operating setting for envisaging the best engine response (i.e., enhanced performance and diminished emissions).

The energy transition necessitates the adoption of new energy sources and sustainable technologies. In this respect, optimizing operating variables can significantly improve the performance of the engine for decentralized electricity generation. Further, this article will guide engine researchers on modelling and optimization techniques for improving the performance of dual-fuel SI engines using PG fuels with blends.

Grape-based PG is also of special interest due to its higher content of hydrogen and nitrogen, as discovered in the experimental work of Stefanos et. al. [39]. Table 2.4 shows the comparative composition of the considered grape-based producer gas with other biomass-producer gas, where grape PG LCV is higher than corncob and eucalyptus PG.

Table 2.4. Distinctions of Grape wood-based PG composition and LHV [39]

Element of PG	**Grape-PG**	**Corncob[170]**	**Eucalyptus[170]**
H_2 (%V/V)	18.63	12.38	13.24
CO (%V/V)	16.94	12.03	10.99
CH_4 (%V/V)	2.02	1.22	2.78
CO_2 (V/V)	6.02	10.67	12.15
N_2 (%V/V)	56.39	58.85	54.62
LHV_{PG} (MJ/kg)	4.52	3.695	4.29
A/F ratio (stoichiometric)	1.02	2.98	2.57