Abstract

Application of suitable alternative fuels for running the already established power conversion technologies, like IC engines for attaining power grid independence, is a very sought-after strategy while reducing the environmental impacts. Moreover, the exhaustible reserves of conventional fossil fuels have already alarmed us to switch to alternative fuels either through sole or blended mode fuel applications. On the other hand, improper management and unsafe disposal of huge sewage sludge volumes is one of the major global environmental concerns and a source of pollution. Sewage sludge (SS) is a solid waste, generated majorly from industrial and municipal wastewater treatments. Even today, the foremost treatment strategies for SS include disposal into oceans, landfills, or incineration. However, these approaches are neither environmental-friendly nor cost-effective. With booming industrial, domestic, and commercial activities, the treatments of these substantial SS volume is anticipated to become significantly challenging. Therefore, towards dealing with the coupled menace of energy crisis and SS management, an efficient waste-to-energy conversion would be very effective. Alternately, the SS is abundant in organic and biodegradable waste content, which on decomposition features flammability potential. SS has been detected as a potential renewable and sustainable biomass source for energy production. It possesses a Higher heating value (HHV) as high as 11.1– 22.1 (MJ/kg). However, the sustainable energy-extraction practices, such as gasification-based electricity power generation using engine coupling, have not been advanced yet. Through this study, the numerical models are developed and initially utilized to simulate the SI engine performance using blends of SS-based Producer Gas and Methane as fuel. The outcomes successfully revealed that relative to neat methane-fuelled engine performance, significant improvement in BMEP and BTE engine performance outcomes, respectively by 10.94% and 27.4%, is achieved through depicted strategies for the fuel blends.

Primary processes to seek effective waste-to-energy conversion are through direct combustion, thermochemical, biochemical, and agrochemical treatment methods. SS can effectively be converted into usable liquid or gaseous fuel through thermochemical conversion routes, like incineration, pyrolysis, or gasification. Recently, the gasification of SS has drawn much attention due to its substantial advantages like, comprehensive destruction of pathogens, microorganisms, swift volumetric reductions, and direct industrial-scale applications for heating and electricity generation. Through gasification, solid organic-based wastes are converted into useful gases and chemicals through thermo-chemical reactions using oxidizing agents such as air, steam, N_2, CO_2, and O_2. Though the Sewage sludge producer gas (SSPG) possesses a relatively lower calorific value compared to many biomass substrates, its utilization in the Internal-combustion engine (ICE) applications has been found to be more effective, convenient, and efficient for waste-to-energy conversion rather than further conversion into di-methyl-ether, synthetic natural gas, or Fischer–Tropsch-based synthetic gasoline.

It has been reported that fuelling pure SSPG to SI engine results in severe problems like unsteady engine run, cycle-to-cycle variations, and frequent misfiring. Thus, to enhance engine performance, modifications will be required including changes in Compression ratio (CR), air/fuel ratio, Start of ignition (SOI), and combustion chamber configurations. Additionally, partial mixing of the PG with conventional-quality or higher-HHV fuels would be supportive in improving the flame propagation speed, in-cylinder combustion effectiveness, and the overall engine performance. Experimental reports have revealed that SI engines fuelled with PG and Methane blends feature better performance and higher peak pressure-cum-power outputs at increased methane-blend fractions. With this particular fuel blend application to SI engine, significant improvement in work cycle stability and engine performance is possible until a 60% blend of PG with Methane, by volume. Whereas further increase in SSPG-fraction leads to hampered combustion stability and engine run, with negative brake power and engine efficiency impacts. On the other hand, increasing the methane blend enhances flame speed and combustion quality. Thus, an advanced ignition system and effective optimization of ignition timings would offer reliable improvements in both the thermal efficiency and the snuck trade-offs. Literature reveals that the relative equivalence ratios ($\lambda \approx 0.6$-1.6) significantly contribute to engine efficiency-power output and exhaust-emissions trade-offs for the dual fuel PG-based engine systems. It is generally observed that the maximum brake power and NO_X emissions are attained at a slightly richer fuel-air mixture (let at λ (air-fuel ratio) =0.9), whereas the Brake Thermal Efficiency (BTE) peaks and CO emissions surge at a slightly leaner mixture (let λ= 1.2~1.4). Multi-objective optimization could certainly address such trade-offs. In terms of limiting the engine power de-rating, successive rescue operations could be implemented such as adjusting the CR to a range of 9.3-17.5, which has been found to reduce the engine power-derating potentially by around 24-38%. The high CR-based engines significantly improve thermodynamic efficiency particularly considering the PG-blends fuelled SI engines. This is attributed to extended combustion situations availed in cylinder at relatively higher local temperature and pressure circumstances. Furthermore, the corresponding decrement in combustion duration when working with PG as fuel is found to significantly limit the improvement in combustion and efficiency. The natural gas-fuelled SI engines generally have lower CR (10-12) and produce 25-28% BTE, while the compression ignition (CI) engine works on higher CRs (18-19) and feature higher thermal efficiency, around 30%. Therefore, towards enhancing engine performance at higher CR, the strategy of blending conventional fuels like gasoline and diesel with a variety of renewable alternative fuels the like PG and natural gas has frequently been considered from a research perspective over the past two decades. Towards an intended increase in both CR and overall efficiency, many innovative strategies like lean burn and intake boosting have also been inspected. However, operations considering various SSPG blends with methane, Miller cycle-based engine, boosting strategies, and requirement for optimization for the various operative parameters like varying equivalence ratios, ignition timings, and other independent innovative parameters still remain a clear research gap. From the inclusive investigations, the optimal operational CR has successfully been predicted to improve from 10/11 CR, for a typical Methane-operated SI Engine, to 13 CR, and thereby significantly improving power and indicated efficiency engine response outcomes.

Certainly, because the experimental investigations with the IC engine systems are absolutely cost-ineffective, the research orientations have also shifted towards the engine performance simulations. The simulation approach is significantly resource-effective when considering small-scale but significant modifications, such as tweaking engine and operative configuration settings and investigating for multiple fuels and different equivalence ratios. From the perspective of effective sewage sludge-waste to end-use electricity generation via engine integration, this research work aims to simulate and investigate the thermal efficiency and power enhancement potential for a high GCR-based unmodified SI engine. In this respect, a quasi-dimensional thermodynamic model is simulated to explore SI engine performance, post a rigorous validation study. For analyzing the trends in engine response variation, and declaring the optimal operating conditions reative to performance improvement and exhaust-emission reductions, this investigation incorporates the processing of simulation-generated dataset through RSM-based statistical analysis and perform multi-objective optimization. Through the SI engine performance modelling, a potential improvement pf 32% in the IMEP has been successfully predicted with implemention of SSPG-methane blends as fuel and considering the unmodified SI engine configuration. The investigation also finds clear improvement in BTE performance outcome by around 27.4% through coupling the Miller Cycle-strategy with the engine simulation model. Thereafter, significant improvement potential in the output brake power, by around 4.2 times, is further evaluated considering the particular fuel blends for SI engine operation through additionally coupling the intake boosting strategy.

Concerning the introduced gaps in research, this simulation program includes the following objectives as a novelty to find out the performance (power, emission, fuel consumptions, efficiency, mean effective pressure) improvement of SI engine and respective optimal operating settings with respect to the following approaches:

- Effect of SSPG blending with methane in various proportions with simultaneously varied inputs of ignition timings and compression ratios.
- Effect of Miller-cycle-based LIVC variations for the 12.0:1 geometrical compression ratio SI engine simulation model constraint.
- Effect of boosting pressure magnitudes at the intake relative to various LIVC settings
- Effects of variations in ERs simultaneous to various LIVC and blend fractions, while intercepting the significant trade-off natures in engine responses.
- Effect of lean mixture combustion on engine responses at simultaneous variations in LIVC settings
- Effects of extending the parametric variations of ER, CR, and IT for various blend proportions of producer gas and propane blends

In light of the aforementioned contemplations, the current thesis is divided into five chapters -

- Chapter 1, presents the background, motivation, and resolving aspects considering SS-based waste-to-energy extraction aspects, and modelling
- Chapter 2, gives the literature review concerning SSPG fuelling SI engine
- Chapter 3, gives significance to the mathematical model and presents development details on the numerical model used
- Chapter 4, presents Results concerning the particular adopted strategies and analysis
- Chapter 5, presents the summarized analysis Conclusions with Outlooks.