Numerical simulation and Investigation of Producer gas based dual fuel mode SI engine performance: Parametric and Optimization study

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By

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Chapter 5. Conclusions and Future Work

The summary of significant analysis findings and the overall conclusions drawn with respect to each research analysis investigation presented in the results section are disclosed in this section. For convenient interception of findings from the sequential operations, presentation of summarized conclusions are presented in the following subsections.

5.1. Corresponding to analysis with blends

With regards to the perspective of straight waste-to-energy conversion, the sewage-sludge-based PG and methane blend compositions are modelled via QDTM to predict the SI engine responses of unmodified specifications. The considered response parameters include power representing terms of IMEP, BP, and BMEP; energy efficiency indicating responses of ITE, BTE, and BSEC; and the emission responses for CO and NO emissions. With the aid of RSM-based statistical analysis of the simulation results, the influential impacts of considered input factors could be intercepted quantitatively. Besides, the fundamental input settings of CR and SOI timings for the specified engine specifications, operating on the particular fuel blends, could be potentially predicted and effectively optimized with respect to performance enhancement and emissions reduction. The following major conclusions could be pointed with regards to with respect to blending SSPG to Methane as fuel through this investigative work.

- Firstly, the quasi-dimensional thermodynamic model has been successfully developed and employed to simulate SSPG-CH_4 fuelled SI engine performance and emission outcomes. The findings of computational simulations are in good accord with data from the literature.
- Optimum operating or decision parameters were: 10 (V%) SSPG, 13 CR, and 34.09^0 (BTDC) setting of SOI. Thereby, the operational CR is successfully predicted to improve from a Methane-operated typical SI Engine setting of 10/11 CR to a higher, 13 CR.

- The optimum engine performance responses were: 35.35% ITE, 6.793 bar IMEP, 28.104% BTE, 4.601 kW BP, 5.487 bar BMEP, 12.81 MJ/kWh BSEC. Optimum predicted engine emissions are 0.645 V% CO and 1967.102 ppm NO.
- The investigated optimal outcomes renderred a significant 32% and 10.94%. improvement in IMEP and BMEP outcomes relative to a typical SI engine performance, with a verified emissions variations.
- According to the RSM and ANOVA, the ITE, IMEP, BTE, BP, BMEP, and BSEC performance responses are predominately affected by the SSPG and CR variation, whereas, CO and NO emission reesponses are majorly affected by spark timing (SOI).

The applied approach in this study develops an investigation aspect regarding future studies on gasification-IC engine integration system performance studies when fuelled with other alternate fuels. Additionally, it facilitates convenient inspection for the simultaneous parametric impacts along with their optimization. Further, the implication of the present study will provide a base for the end-users and researchers to adopt this numerical analysis method as a feasible approach toward utilizing the PG produced from sewage sludge gasification. Because, the present simulation performance results predict improved and better performance result, by utilizing and analyzing the engine strategies an involvement of LIVC, CR, Ignition time, Methane-blending, Intake boosting, and applying the multi-objective optimization. Subsequentely, from the graphs and table, the present study will provide a base for the end-users and researchers to adopt this numerical analysis method as a feasible approach toward utilizing the sewage sludge based PG fuel.

5.2. Corresponding to Miller-cycle operation

The performance and emission parameters for the stoichiometric SSPG and CH_4 mixture fuelled SI engine were similarly coded for 1500 RPM and 12 geometric CR engine model, via the QDTM-based principle. The followed RSM optimization, considering SSPG blends, LIVC, and SOI input factors. Based on the RSM-based regression modelling and ANOVA analysis, the following significant findings could be professed.

- A trade-off pattern between thermal efficiency (ITE) and output powers (IP, BP) was observed for varying SSPG and LIVC input parameters.
- Maximum BTE of 28.38% and ITE of 37.38% are attained at separate lateness values of IVC. These efficiency outcomes renderred a significant 27.4% improvement in the BTE response compared to neat-methane run typical SI engine performance outcomes.
- An ignition timing (SOI) close to the obtained optimum (34.03^o CA-BTDC) should result in both enhanced engine performance efficiency and power output.
- A trade-off pattern between carbon mono-oxide (CO) and nitrogen mono-oxide (NO) were verified to be consistent relative to a couple of referred experimental studies. Low CO emissions (< 0.74 V%) evolve at low SSPG-blend (<45 %) and SOI (<40^o), with preferably greater LIVCs (70^o, 80^o and 90^o); whereas, low NO-release (<2700 ppm) is feasible at higher SSPG blends (>35 %), low LIVC (<70^o aBDC), and up to 40^o BTDC SOI.
- The RSM-based optimization predicted 64.7 (V%) SSPG, 70.33^o (CA-ABDC) LIVC, and 34.03^o (BTDC) SOI as the optimum operating settings for this Miller Cycle-based investigation.
- The corresponding optimum responses were: 36.46% ITE, 5,17 (kW) IP, 27.94% BTE, 4.08 (kW) BP, 12.671 (MJ/kWh) BSFC, with 0.688 (V%) CO with 1456.93 (ppm) NO.
- LIVC, though introduced to enhance efficiency, was observed to significantly influence the engine power (IP, BP) as evident through the ANOVA analysis.
- CO and NO emissions are found to be significantly influenced from the SOI variations

Overall, the numerical thermodynamic-based model and the subsequent data analysis through ANOVA analysis and RSM optimization revealed that the methane and PG blends-fuelled SI engine enhances performance and minimizes exhaust emissions if the engine runs close to the optimized operating conditions.

5.3. Corresponding to boosted intake

This analysis utilized QDTM to reveal the impacts of simultaneous variations in Pressure-boosting of intake charge at IVC (PIVC), SSPG-blend fraction, and Late-inlet valve closures (LIVC) on the engine responses. According to the ANOVA-based analysis of simulation outcomes, variations in PIVC and LIVC significantly influenced power output and Brake-specific energy consumption (BSEC)-responses. Major trade-off patterns were observed between engine output power and the efficiency respective to the LIVC variations, and CO-NO emissions respective to the SSPG variations. As simulation results are consistent with data from the literature, the following consistent conclusions could be declared:

- A maximum indicated thermal efficiency of 41.93 % could be obtained for peak settings of PIVC, SSPG-blend fraction, and LIVC, and the maximum BP improved by around 4.2 times with intake boosting relative to a typical CH_4-run SI Engine mode.
- Optimum intake-boosting, SSPG-blending and Miller Cycle-inducted LIVC parameter were predicted as much as 3 bars of PIVC, 76.94 (V%) and about 77^0 (CA-ABDC), respectively.
- RSM-based optimum responses were 21.35 bars IMEP, 40.46% ITE, 16.8 kW of BP, 9.483 kJ/kWh of BSEC, 20.04 bars BMEP, and 0.085 (V%) of CO, with 3094.16 ppm of NO emissions.
- Cumulative composite desirability of around 0.712 was acquired through the RSM-based optimal solution.

- Indicated efficiency was significantly affected by LIVC variations rather than by intake boosting.

The composite desirability remains above 0.706 if the engine runs with 3 bars of peak intake boosting and simultaneous SSPG and LIVC settings close to 74-80 (V%) and 80 (CA-ABDC), respectively. In this respect, the current study implications would serve as the basis for researchers to adopt numerical evaluation of integrated sewage sludge gasified gasification-IC engine systems.

5.4. Corresponding to variable equivalence ratio

Equivalence ratios (0.8, 0.9, 1.0, and 1.1), SSPG-blends (25%, 50%, 75%), and Late-inlet valve closures in terms of after BDC (50^0, 60^0, 70^0,80^0, 90^0CA) were considered as operating parameters to determine the performance (IMEP, BP, BTE, BSEC) and emission (CO, NO) characteristics for the DF mode engine simulation. According to ANOVA-analyzed results, the variations in SSPG and LIVC laid greater influences on performance efficiency and output power respectively. Engine efficiency and power output showed a trade-off pattern. Thus, to consolidate the performance-emissions trade-off, optimization has been performed using the design of experiment (DOE) based response surface methodology (RSM) statistical approach. Accordingly, the following major conclusions have been drawn:

- While SSPG-blend fractions increase, BTE increases, BSEC decreases but BP marginally decreases. On the other hand, while LIVC increases, BTE increases but IMEP and BP decrease.
- The major trade-offs of efficiency and power were observed corresponding to SSPG and ER input parameters. Initially, BTE increases with the ER increments till 0.9 ER, attains 28.76%, and thereafter it decreases with further ER increment.

- The simulated CO-NO emission tradeoffs were found suitaby verifying the observed CO-NO tradeoffs, of an experimental reference work, for neat-Methane fuel based SI Engine performance outcomes especialy considering the richer intake fuel mixture. For instance, 0.49 times (≈50%) decrease in NO emission with respect to 34.7% increase in CO for full-range increase in SOI parameter.
- Significant tradeoffs are also observed among the CO and NO emissions at the ER-variation range of 0.9 to 1.1. ER increase resulted in around 1.94 times increase in CO-emission and 6.64 times decrease in NO-emissions.
- The maximum brake thermal efficiency was 28.76% at 0.9ER, 75% PG, and LIVC 70^0ABDC, while the maximum brake power was 4.95 kW at 1.0 ER, 25% SSPG, and 50^0ABDC-LIVC.
- Optimum operating input parameters were found as 0.814 ER, 68.237% SSPG, and 55.93^0 (ABDC-CA) LIVC. The correspondingly predicted responses of IMEP, BP, BTE, BSEC, CO, and NO were 5.906 bar, 3.86 kW, 28.6%, 12.59 MJ/kWh, 0.135 V%, and 2045.29 ppm respectively, with a cumulative composite desirability of 0.843.

It is found that enhancement in performance and minimization of exhaust emissions can be obtained if the engine operates with optimized operating conditions.

5.5. Lean-burn performance improvement analysis

Performance and emission parameters for the DF SI engine fueled with CH_4 and PG at a lean, 0.8 ER, 1500 RPM, and 12 CR, are modelled. As per the statistical investigation of the simulation-obtained outcomes, LIVC variations had a substantial impact on the engine's performance, whereas the varying start of ignition (SOI) and amount of SSPG blending (Blend%) had a significant impact on emissions.

- As LIVC increased from 50^o to 90^o (ABDC), modelled ITE increased, but BSFC was also found to increase.
- The optimum magnitude of operating conditions as SSPG-blend, LIVC, and SOI were obtained to be 75%, 50^o ABDC, and 35.82^0 BTDC, respectively.
- The optimum values of IMEP, BP, BSFC, ITE, CO, and NO were observed to be 6.118 bar, 4.033 kW, 0.3773 kg/kWh, 35.6858%, 0.0966 V%, and 1366.24 ppm, respectively.
- ITE, IMEP, BP, BMEP, and BSFC are predominantly affected by the LIVC variations, whereas, CO and NO emissions are majorly affected by SOI and blending extent.

As per the future scope, the present numerical model will certainly be helpful in thermodynamic and experimental studies on SI engines when fueled with other alternate fuels. Moreover, till now a combination of three independent factors was being investigated constrained to achieving greater desirability outcomes. The future scope incorporated optimization performances with respect to wider independent input factors.

5.6. Grape wood-PG and Propane blends' QDTM analysis

This study uses numerical modeling and multi-objective optimizations to explore performance enhancement and emission reductions for a dual-fuel SI engine. The approach of using four independent parameters - Blending-fraction (BF), Equivalence ratio (ER), Compression ratio (CR), and Ignition timing (IT) as decision parameters was executed in simulation and through RSM-optimization to estimate the optimal performance (BMEP and BSFC) and emission parameters (CO and NO). The optimality of responses was compared respective to a case of letting the independent parameters be unconstrained, and another case of letting only the BF-operative parameter be constrained towards minimization (or PG-blend maximization), wherein the engine model delivers very comparable outputs. The following major conclusions were drawn from the investigated study

- Increasing the propane-blending enhances the performance responses, and a simultaneous equivalence ratio increase significantly reduces the NO emission.
- An equivalence ratio of more than 1.08 could effectively counter the drawback of engine power-derating.
- Regression models were found highly accurate for predicting the output responses with ANOVA justifying the response sensitivities towards operating parameters' variations.
- Inline with the results depicted from surface plots, ANOVA results approved that the BTE and BSFC responses are most influenced by the BF*ER two-way interaction.
- Through ANOVA, ER and IT were also found most influencing factors for the CO and NO emission responses
- Optimal independent operating variables for a general case of optimization were found as 79.998(V%) BF, 1.032 ER, 13.99 CR, and slightly advanced IT of 41.42^{o} (CA-BTDC).
- Desiring for more Grape-PG substitution resulted in shifting of optimal responses to 53.853 V% of PG-blend (or, 46.147 BF), greater ER (1.036), and slightly more advanced IT (43.20^{o} CA-BTDC).
- Optimum dependent response parameters were found as 27.47% BTE, 7.51(bars) BMEP, 0.3153(kg/kWh) BSFC performances, and 1.166(V%) of CO and 1407.5(ppm) NO emissions.
- Individual desirabilities for the responses showing significant trade-offs like CO-NO and BTE-BMEP, show reduced individual desirability values.
- Composite desirability through the optimization was 0.859, whereas, with the setting of propane blend-fraction for minimization, the composite desirability was reduced to 0.728. With the feasible operating inputs and significant response outputs, it is

recommended from the present study that Propane and grape-based PG could feasibly become a viable biomass-based energy source.

From the simulation and optimization results perspective, higher than 60% and 53.85 V% of PG-blend respectively with propane tends to higher derating of BMEP to respective brake power. Correspondingly it can be suggested that a lower blending ratio of PG with propane is beneficial for the brake power, however, since NOx emission is found to be increasing order, the preparation of fuel mixtures requires more precautions to limit the emissions.

Furthermore, to efficiently run the dual fuel engine system, besides accuracy in mixing, and maintaining the PG gas composition, the PG purification, fuel storage, and handling precautions must be taken care. For a proper IC Engine functioning, the acceptable tar and particulate concentration must remain lower than 100 mg/Nm^3 and 50 mg/Nm^3. However, fixed bed gasifiers generate particulate matter in 50~500 mg/Nm^3, while the tar components range in 50~1000 mg/Nm^3. Therefore, purification of PG becomes essential [231]. The purification of producer gas is crucial to ensure the efficient and reliable operation of the dual-fuel systems. Tar and particulates can cause clogging, damage to engine components, and decrease combustion efficiency, while sulphur compounds can lead to corrosion. Effective purification may involve a series of filters, scrubbers, and dryers to ensure the gas is clean enough for stable and long-lasting dual-fuel operation [232]. A cyclone separator is usually employed to remove particulate matter greater than 5μm. It follows a wet scrubber to reduce PG temperature and enable condensation that removes the corrosive sulphur and other halogenous compounds in the producer gas [233]. Although, the dual fuel engine application limits its usage in automotive vehicle systems, particularly the stationary engine-genset operations for generate electricity, further research progress towards efficient and low-cost purification-cum-storage would allow its usage in transportation fuel as well.

5.7. Scope for future work

As the modelling methodology is effective in mimicking the uneconomic experimental approach with satisfactory accuracy, the future scope for this research work is towards inspecting the impacts of technical replacements to the traditional applications, like:

- analyzing various valve-system changes, along with the different operating settings, such as- boosting the intake, varying equivalence ratio, compression ratio, and spark positions.
- analyzing various potential alternative fuelling agents, such as hydrogen, methane, ethanol, and biogases, as well as their blends.

In addition to the presented gaps, the limitations of the adopted methodology also need to be mentioned along with expected resolution routes and potential research possibilities.

- Although the QDTM is more consistent the 1-d model and requires lesser computational demand the 3d-CFD model, it still is less reliable than the 3D CFD model, while requiring rigorous calibration efforts for the involved QDTM sub-models with respect to new fuel grades.
- The Gas-dynamics also needs to be included in the modelling with respect to the considered minor fluid dynamic models of Swirl and Squish in-cylinder gas-dynamics, and generate an analytically more consistent result.
- The filtration or inclusion of the membrane-based separation strategy for the generated producer gas from gasification is also of a significant research potential and would be progressed with.
- The techno-economic threshold of SS-feed for determining the profitability index and Life-Cycle Assessment of the gasification unit would be required to be found and sorted out corresponding to SS quality and availability, and gasification rate. It would confirm the economic viability for the adopted SSPG-based energy extraction method.

- Implementation of R&D efforts and economic incentive policies would be necessary to be reviewed for successful implementations of the examined strategies. This is because the involved SS characterizes distinct composition types with varying availability and across countries.

Moreover, the strategy adopted in this work is expected to enable significant convenience in inspecting the energy conversion potential regarding the alternative fuels and their waste-to-energy conversion aspect. At a broader scope, the future aspects of this research work regarding sewage sludge management through utilization of the gasification would shift towards predicting the IC engine performance via hydrogen applications. Through the simulation approach, the uncertainties and risks with such operational wellness when applying the novel fuel materials would be addressed alongwith inspection of various operational strategies towards improving the engine performance. Technological advancements for the production of hydrogen from sewage sludge using advanced gasification technology are also sought within the future scope of this thesis. This is very significant since hydrogen synthesis is becoming comparable to fossil fuel production [95]. According to Midilli et al. ([96], 2002), the producer gas yielded through gasification comprises around 10%-11% hydrogen, and it can be further used in fuel cells after separation. The producer gas-comprised methane might also be turned into hydrogen, and the CO may be oxidized for the reduction of hazardous emissions[40]. Other aspects under the broader scope include:

- Further enhancement of the FORTRAN-coded simulation model to accomplish the CO_2, and NO_X-emission predictions with greater precision, using the chemical kinetics and multi-zone modelling approaches.

- RSM and AI-based Optimization of Dual-fuelled engine's operating conditions to harvest best performance and emissions responses and declare the better optimization modules.
- CFD-based approach towards analyzing the processes of gasification, solar association, and waste heat management
- ASPEN PLUS implementation for gasifier operation modelling.
- Experimental investigation on the gasifier-integrated Burner or IC engine applications.

In order to guide novice engine investigations, this investigation critically elucidates the modelling and optimization technique for enhancing the dual-fuelled mode SI engine performance. This work is also expected to provide effective recommendations for evaluation and engine performance modelling with regard to the utilization of other alternative renewable fuels.