Simulation of effect of bed temperature over producer gas composition using ASPEN PLUS, its experimental validation and emission characteristics of an IC engine

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Abstract. Biomass is the source of energy that is generated from organic materials, which has the capacity to generate power in different means. Gasification is the technique that converts biomass materials into combustible gas by undergoing chemical reactions at high temperature with a controlled oxygen availability. The objective of this study is to determine the performance of downdraft gasifier and emission characteristics of IC engine using producer gases at various bed temperatures. The satisfactory performance of gasification, is theoretically attaining at a gasification temperature range of 500°C to 750°C. The temperature dependency of gasification process in the performance of downdraft gasifier is studied for different types of feed stocks. The downdraft gasifier is simulated using process simulation software ASPEN PLUS. It is found that at higher gasification temperatures the quality of producer gas increases considerably. The exhaust emission characteristics and efficiencies of engine with producer gas are comparable with normal gasoline exhaust characteristics.

Keywords: Gasifier, emission, IC engine

1. Introduction

Energy crisis and pollution are the main threats that we are facing now. Researches are going on at various parts of the world to develop an alternative energy source which has lower emission characteristics and better performance. Hydrogen which is considered as the future energy source due to its highest energy to weight ratio compared to any fuel. Gasification is considered to be as a better technology used to produce hydrogen from organic materials. By gasification process a considerable amount of organic waste materials can be converted into useful energy. Pyrolysis is the main chemical process which takes place in gasification process. It is the thermal degradation of biomass into combustible solid char, liquid bio oil by chemical processes with limited supply of oxygen.

Gasifiers are instruments used to develop gasification process. There are different types of gasifiers available, among them fluidized bed gasifiers and downdraft gasifiers are widely used based on nature of the feed. For solid feeds or for those feeds which can be solidified easily, can use downdraft
gasifiers and those feeds which can powdered easily, can use fluidized bed gasifiers. Emission characteristics of the IC engines using different quality producer gases as fuels are to be studied, since producer gas is considered to be as an alternative fuel source of near future. If the emission characteristics are improved than conventional gasoline fuel, then producer gas can be used as alternative fuel, even there is a reduction in efficiencies or power outputs. Each feed gives different quality producer gases at different gasification temperatures. Current work deals with study of producer gas quality, performance and emission characteristics of solid feed coconut shell and fibrous feed at three different gasification temperatures using downdraft gasifier.

Rao et al. [1] carried out experiments on counter current fixed bed gasifier with different solid fuels to compare the efficiency of gasifier as well as suitability of dried fruit petals for gasification in comparison with gasification of wood chops and CSS using the very same gasifier under similar operating conditions.

Rajvanshi [2] mentioned about basics of gasification in the fourth chapter of his book ‘Alternative Energy in Agriculture’. In the same, briefly described types of gasifiers, chemical reactions of gasification, different process zones, and yield products of gasification with its approximate percentage with different known feeds. The method of applying producer gas in SI and CI engines and the efficiencies that can be achieved from these engines.

Basu [3] in his text book named “Biomass gasification and pyrolysis practical design” explained in detail about gasification process and various related tests for the calculation of performance of the gasifier. He detailed about relevance and art of gasification. The practical approach of gasification and practical problems deals with gasification process.

Atnaw et al. [4] carried out simulation work on downdraft gasifier with oil palm fronds using aspen plus. He conducted the work on gasifier with different operating pressures, moisture contents etc. He simulated the gasification with various pressure ratios below 5 bar and optimised. The model study revealed the effect of moisture content, pressure ratio in gasification process.

Mathieu and Dubuisson [5] carried work on Performance analysis of a fluidized bed gasifier, using aspen plus process simulator. Used wood as feed material. Minimisation of the Gibbs free energy is the thermodynamic model used for process simulation.

Chittaranjan Panda [6] in his thesis simulated fluidized bed gasifier using aspen plus simulator for rice husk gasification. Studied the effect of reactor temperature, equivalence ratio and steam to biomass ratio on composition of product gas. The results showed hydrogen concentration in the producer gas increases with increase in temperature.

| Nomenclature     | Description                           | Unit       |
|------------------|---------------------------------------|------------|
| CV               | Calorific Value                       | kJ/kg      |
| LHV              | Lower Calorific Value                 | kJ/kg      |
| P                | Electrical load                       | W          |
| CGE              | Cold Gas Efficiency                   | %          |
| V<sub>i</sub>    | Volume flow rate                      | m³/s       |
| m<sub>i</sub>    | Mass flow rate                        | kg/s       |
| X<sub>i</sub>    | Weight percentage                     | %          |
| x<sub>i</sub>    | Mass percentage                       | %          |
| δ                 | Density                               | kg/m³      |
| BTE              | Brake thermal efficiency              | %          |
Forero-Núñez and Sierra-Vargas [7] conducted experiment on heat transfer analysis using thermal imaging. Heat transfer by convection and radiation is mentioned in this study by incorporating some dimensionless numbers. Coconut shell is used for the analysis. The biomass consumption was 8 kg/hr. which gives a thermal output of 3862 kW and an electrical efficiency of 20.71%. Cold Gas Efficiency depended on producer gas volumetric flow and heating value of producer gas. Aspen plus is a typical user-friendly process simulation software, which can predict the nature of the process and its outcomes. Downdraft gasification process is simulated using Aspen plus, which is same as the experimental set up. Aspen plus simulation results are validated using experimental results. The emission characteristics of an IC engine with different quality of producer gases with feed stocks are studied and get it compared with conventional gasoline fuel.

2. Feed characteristics
The proximate and ultimate analysis of feeds are given in table 1.

| Feed characteristics (wt. %) | Coconut shell | Sugarcane waste |
|------------------------------|---------------|-----------------|
| Moisture                    | 8.067         | 14.60           |
| Fixed carbon                | 15.783        | 10.50           |
| Volatile material           | 73.65         | 73.1            |
| Ash                         | 2.5           | 1.8             |
| Carbon                      | 45.26         | 43              |
| Hydrogen                    | 5.72          | 6.03            |
| Nitrogen                    | 0.13          | 0.77            |
| Oxygen                      | 48.89         | 50.08           |
| Sulphur                     | traces        | 0.12            |

3. Experimental Setup
Figure 1 shows the downdraft gasifier used for experimental studies, in which the main part is its reactor itself. Then the producer gas flows through a cyclone, water scrubber, solid trap for removing solid wastes like ash, solid carbon. A chiller is provided at the exit for reducing the temperature of the producer gas below atmospheric temperature in order to connect it with the engine system. An orifice plate and u tube manometer is in the system to calculate producer gas consumed by the engine.

![Figure 1. Downdraft gasifier](image)

An exhaust gas analyzer is used to study emission characteristics and a calibrated producer gas analyzer is used to analyze the producer gas developed by gasification process.
4. Simulation Model

Figure 2 shows the process model of downdraft gasification process. The simulation consists of three reactors, cyclone, scrubber and a chiller. The gasification process is done in three reactors and the rest is arranged for removing the solid components present in the producer gas at exit. The Feed must be well dried before firing the gasifier. Even though it is dried it contains small amount of moisture, which is removed in drying zone which is simulated using the reactor R-stoic. All feeds in gasification process is considered as non-conventional by aspen plus, so feeds must be made conventional by using R-Yield reactor.

![Figure 2. ASPENPLUS simulation model](image)

The yield is done by simulation based on its ultimate and proximate analysis. The gasification is done by the reactor R-gibbs, which works on Gibbs free energy concept. The cyclone and water scrubber are used to remove solid components from producer gas and chiller is used to get producer gas below atmospheric temperature.

5. Results and discussions

5.1 Calorific values of biomasses

The calorific value or heating value of biomass can be calculated by using the equation. The calorific value of feeds is given in table 2.

\[ CV = 0.3494X_C + 1.1783X_H + 0.0053X_S - 0.151X_N - 0.1034X_O - 0.0211X_{ASH} \] [3][7].

| Biomass         | Calorific value (MJ/kg) |
|-----------------|-------------------------|
| Coconut shell   | 18.27                   |
| Sugarcane waste | 15.34                   |

5.2 Producer gas composition

From table 3 and table 4 the producer gas composition, both experimental and simulation can be compared, for coconut shell as well as sugarcane waste. The experimental and simulation results are compared for both the feeds by assuming gasification process as ideal in simulation. It can be seen that the simulation predicts the nature of producer gas.

As the gasification temperature increases, the mass flow rate of both hydrogen and carbon monoxide increases whereas mass flow rate of methane and carbon dioxide decreases for both the feeds. The results of simulation and experiment are comparable.
Table 3. Producer gas composition, both experimental and simulation of coconut shell feed

| Temperature (°C) | 625°C | 675°C | 725°C |
|-----------------|-------|-------|-------|
| Components (kg/hr.) | Simulation | Experimental | % Difference |
| H<sub>2</sub> | 0.206 | 0.1516 | 35 |
| CO | 2.382 | 2.05 | 16 |
| CO<sub>2</sub> | 2.435 | 2.344 | 3 |
| CH<sub>4</sub> | 0.267 | 0.3411 | 21 |

Table 4. Producer gas composition, both experimental and simulation of sugarcane waste feed

| Temperature (°C) | 625°C | 675°C | 725°C |
|-----------------|-------|-------|-------|
| Components (kg/hr.) | Simulation | Experimental | % Difference |
| H<sub>2</sub> | 0.177 | 0.1204 | 47 |
| CO | 1.690 | 1.54 | 9 |
| CO<sub>2</sub> | 2.212 | 2.33 | 5 |
| CH<sub>4</sub> | 0.147 | 0.232 | 36 |

The composition of producer gas is predictable by using aspen plus process simulator. It is evident from the composition of producer gas that the quality is superior at higher gasification temperatures.

5.3 Density of producer gases
Density of producer gas is determined by hydrogen and carbon monoxide contents in the producer gas. As the amount of hydrogen and carbon monoxide increases, quality increases and density decreases. Table 5 and table 6 shows the density of producer gases at different gasification temperatures.

Table 5. Density of coconut feed producer gas

| Temperature (°C) | Density (kg/m<sup>3</sup>) |
|-----------------|-----------------------------|
|                 | Simulation | Experiment | % Difference |
| 625             | 0.97625 | 1.0349 | 5 |
| 675             | 0.94432 | 0.98598 | 4.2 |
| 725             | 0.8786 | 0.901332 | 2.5 |
Table 6. Density of sugarcane waste feed producer gas

| Temperature (°C) | Simulation | Experiment | % Difference |
|------------------|------------|------------|--------------|
| 625              | 0.9942     | 1.12       | 11           |
| 675              | 0.9625     | 0.9999     | 3.7          |
| 725              | 0.9358     | 0.97       | 3.5          |

5.4 Calorific values of producer gas

Table 7 and table 8 shows calorific values of producer gas at different gasification temperature, for both the feeds. As temperature increases quality increases, calorific value increases. Equation used to find calorific value of producer gas is

\[
\text{LHV}_{\text{SYNGAS}} = (x_{\text{CO}} \times \text{LHV}_{\text{CO}}) + (x_{\text{H}_2} \times \text{LHV}_{\text{H}_2}) + (x_{\text{CO}_2} \times \text{LHV}_{\text{CO}_2}) \tag{2}[3]
\]


Table 7. Calorific Value of coconut shell producer gas

| Temperature (°C) | Simulation | Experiment | % Difference |
|------------------|------------|------------|--------------|
| 625              | 3.6        | 2.705      | 33           |
| 675              | 4.75       | 3.8        | 25           |
| 725              | 5.225      | 4.66       | 12           |

Table 8. Calorific Value of sugarcane waste feed producer gas

| Temperature (°C) | Simulation | Experiment | % Difference |
|------------------|------------|------------|--------------|
| 625              | 3.16       | 1.7        | 85           |
| 675              | 3.18       | 2.5        | 27           |
| 725              | 4.03       | 3.6        | 12           |

5.5 Cold gas efficiency (CGE)

Table 9 and table 10 shows cold gas efficiency of gasifier for different quality producer gases, both experimental and simulation. The maximum CGE attained by coconut shell feed producer gas is 71% experimentally and 77% by simulation. Similarly 49% and 60% for sugarcane waste.

Table 9. CGE of coconut shell producer gas

| Temperature (°C) | Simulation | Experiment | % Difference |
|------------------|------------|------------|--------------|
| 625              | 66         | 54         | 22           |
| 675              | 71         | 58         | 22           |
| 725              | 77         | 71         | 8            |

Table 10. CGE of sugarcane waste feed producer gas

| Temperature (°C) | Simulation | Experiment | % Difference |
|------------------|------------|------------|--------------|
| 625              | 51         | 29         | 75           |
| 675              | 57         | 39         | 46           |
| 725              | 60         | 49         | 22           |

CGE = Flow of energy in gas /Energy contained in biomass
CGE = (V_{syngas} \times LHV_{syngas}) / (m_{biomass} \times CV_{biomass}) [3][7]

5.6 Electrical efficiency of gasifier
Table 11 shows electrical efficiency of gasifier for different quality producer gases, experimentally. The maximum $\eta_{\text{electrical}}$ attained by coconut shell feed producer gas is 10%. Similarly 4.2% for sugarcane waste.

$\eta_{\text{electrical}} = \text{Electrical power output} / \text{Energy contained in biomass}$

\[
\eta_{\text{electrical}} = P / (m_{\text{biomass}} \times CV_{\text{biomass}}) \quad [3][7]
\]

| Temperature (°C) | Coconut (%) | Sugarcane (%) |
|------------------|-------------|---------------|
| 625              | 6.03        | 2.27          |
| 675              | 8.26        | 3.3           |
| 725              | 10          | 4.2           |

5.7 Brake thermal efficiency (BTE)
Table 12 shows BTE of IC engine with different quality producer gas, and with both the feeds. It is compared with the gasoline BTE over the same IC engine.

| Load (W) | Gasoline | Coconut (725°C) | Coconut (675°C) | Coconut (625°C) | Sugarcane (725°C) | Sugarcane (675°C) | Sugarcane (625°C) |
|----------|----------|-----------------|-----------------|-----------------|-------------------|-------------------|-------------------|
| 0        | 0        | 0               | 0               | 0               | 0                 | 0                 | 0                 |
| 200      | 5.51     | 3.9             | 3.7             | 3.2             | 3.1               | 3.1               | -                 |
| 400      | 10.11    | 6.9             | 6.5             | 6.2             | 5.8               | 5.62              | -                 |
| 600      | 12.11    | 10.4            | 9.8             | 9.3             | 8.2               | -                 | -                 |
| 800      | 15.18    | 12.51           | 12.52           | -               | -                 | -                 | -                 |
| 1000     | 17.42    | 13.8            | 12.87           | -               | -                 | -                 | -                 |
| 1200     | 17.65    | 14.5            | -               | -               | -                 | -                 | -                 |
| 1400     | 18.09    | 16.1            | -               | -               | -                 | -                 | -                 |
| 1600     | 16.56    | -               | -               | -               | -                 | -                 | -                 |

The maximum BTE attained by gasoline fuel is 18.09% whereas the maximum BTE by producer gas is 16.1% for producer gas obtained from coconut feed at 725°C is used.

BTE = Output power of engine / heat input

Output power of engine = Output power measured / ($\eta_{\text{coupling}} \times \eta_{\text{generator}}$)
Where $\eta_{\text{coupling}} = 90\%$ and $\eta_{\text{generator}} = 80\%$

Heat input = gas consumed $\times$ calorific value of producer gas

5.8 Emission characteristics
Table 13 to table 16 shows different emission characteristics of producer gas fuels, and compares it with gasoline fuel emission. By comparing CO_2 emission is high in the case of producer gas emission, whereas CO, NOx, HC emissions are very low for producer gas fuel, as compared to gasoline fuel emission.
Table 13. CO₂ Emission characteristics (% Volume)

| Load (W) | Gasoline | Coconut | Sugarcane |
|----------|----------|---------|-----------|
|          | (725°C)  | (675°C) | (625°C)   |
|          | (725°C)  | (675°C) | (625°C)   |
| 0        | 4.2      | 9.72    | 8.78      | 8.8       | 6.58 | 6.3 | -     |
| 200      | 4.3      | 9.99    | 9.58      | 9.6       | 7.82 | 7.4 | -     |
| 400      | 4.5      | 10.3    | 10        | 9.61      | 8.42 | 8.12 | -     |
| 600      | 4.7      | 10.59   | 10.6      | 11        | 9.82 | 8.67 | -     |
| 800      | 4.8      | 11.86   | 11.7      | 11.2      | -    | -   | -     |
| 1000     | 5.05     | 12.68   | 12.3      | -         | -    | -   | -     |
| 1200     | 5.15     | 12.97   | 12.82     | -         | -    | -   | -     |
| 1400     | 5.25     | 13.98   | -         | -         | -    | -   | -     |

Table 14. CO Emission characteristics (% Volume)

| Load (W) | Gasoline | Coconut | Sugarcane |
|----------|----------|---------|-----------|
|          | (725°C)  | (675°C) | (625°C)   |
|          | (725°C)  | (675°C) | (625°C)   |
| 0        | 4.22     | 0.92    | 0.94      | 0.96      | 0.94 | 0.9 | -     |
| 200      | 4.24     | 0.47    | 0.53      | 0.63      | 0.7  | 0.84 | -     |
| 400      | 4.29     | 0.29    | 0.36      | 0.45      | 0.76 | 0.84 | -     |
| 600      | 4.34     | 0.18    | 0.21      | 0.33      | 0.72 | 0.81 | -     |
| 800      | 4.38     | 0.18    | 0.19      | 0.21      | -    | -   | -     |
| 1000     | 4.46     | 0.16    | 0.18      | -         | -    | -   | -     |
| 1200     | 4.61     | 0.14    | 0.15      | -         | -    | -   | -     |
| 1400     | 4.72     | 0.13    | -         | -         | -    | -   | -     |

Table 15. HC Emission Characteristics (PPM)

| Load (W) | Gasoline | Coconut | Sugarcane |
|----------|----------|---------|-----------|
|          | (725°C)  | (675°C) | (625°C)   |
|          | (725°C)  | (675°C) | (625°C)   |
| 0        | 162      | 78      | 118       | 125       | 92   | 127 | -     |
| 200      | 161      | 71      | 114       | 121       | 78   | 106 | -     |
| 400      | 156      | 35      | 53        | 106       | 69   | 88  | -     |
| 600      | 141      | 29      | 33        | 71        | 54   | 82  | -     |
| 800      | 135      | 20      | 29        | 50        | -    | -   | -     |
| 1000     | 128      | 20      | 22        | -         | -    | -   | -     |
| 1200     | 131      | 18      | 20        | -         | -    | -   | -     |
| 1400     | 134      | 16      | -         | -         | -    | -   | -     |

Table 16. NO Emission Characteristics (PPM)

| Load (W) | Gasoline | Coconut | Sugarcane |
|----------|----------|---------|-----------|
|          | (725°C)  | (675°C) | (625°C)   |
|          | (725°C)  | (675°C) | (625°C)   |
| 0        | 29       | 14      | 7         | 5         | 8    | 4   | -     |
| 200      | 33       | 15      | 7         | 7         | 8    | 5   | -     |
| 400      | 36       | 15      | 8         | 7         | 9    | 5   | -     |
| 600      | 41       | 16      | 8         | 8         | 9    | 5   | -     |
| 800      | 46       | 16      | 9         | 8         | -    | -   | -     |
| 1000     | 53       | 16      | 9         | -         | -    | -   | -     |
| 1200     | 60       | 19      | 10        | -         | -    | -   | -     |
| 1400     | 65       | 19      | -         | -         | -    | -   | -     |

Lower BTE of producer gas fuel can be compensated with better emission properties of producer gas when compared with conventional gasoline fuels.
6. Conclusions
Using ASPEN PLUS process simulator, a model for biomass gasification with downdraft gasifier was simulated. Coconut shell and sugarcane waste were taken as feed materials. An experimental study of biomass gasification was conducted using a fixed bed downdraft gasifier using coconut shell and sugarcane waste as feeds. Experimental results are used to validate simulation results.

A series of experiments and simulations were performed to investigate the effect of gasifier bed temperature or the gasification temperature over the quality of producer gas. The mass flow of H₂, CO, CH₄ and CO₂ were calculated from experimental results and from simulation results. All other gases in the atmosphere is assumed to be present in lower concentration.

The results show that the hydrogen concentration in the producer gas increases rapidly with increase in temperature (600-750°C) at constant equivalence ratio. The calorific value of producer gas and cold gas efficiency of the gasifier shows good agreement between experimental and simulation results. The electrical efficiency of the gasifier is within the theoretical range. The brake thermal efficiency, exhaust gas characteristics of the engine is compared with gasoline fuel and producer gas. The results indicate that a good quality producer gas is a promising substitute for gasoline.

The coconut shell feed gave superior results with downdraft gasification rather than sugarcane waste feed, which effects the performance of gasifier as well as the engine. The variation is due to the fibrous nature of the sugarcane waste.

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