

**STUDY OF PERFORMANCE AND EMISSIONS OF A
DUAL FUEL ENGINE RUN WITH COTTON STALKS AND
DIESEL**

A Thesis Submitted in Fulfillment of the Requirement for the Award of the Degree of

Doctor of Philosophy
In
Mechanical Engineering

Submitted By

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DECLARATION

I, **Ashish Malik** hereby certify that the work which is being presented in this thesis, entitled “**Study of Performance and Emissions of a Dual Fuel Engine Run with Cotton Stalks and Diesel**” in fulfillment of the requirements for the award of the Degree of Doctor of Philosophy submitted at Mechanical Engineering Department, Thapar University, Patiala is an authentic record of my own work carried out during a period from **January, 2010 to December, 2016** under the supervision of **Dr. S.K. Mohapatra**, Senior Professor & Head, Mechanical Engineering Department, Thapar University, Patiala.

The matter presented in this thesis has not been submitted anywhere for the award of any other degree by this or any other University/Institute.

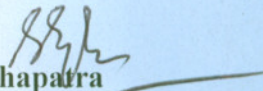
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CERTIFICATE

This is to certify that this thesis, entitled “**Study of Performance and Emissions of a Dual Fuel Engine Run with Cotton Stalks and Diesel**” embodies the work carried out by **Mr. Ashish Malik, Registration No.: 0950908003**, himself under my supervision and that this work has not been submitted elsewhere for any other degree.


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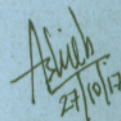
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(ASHISH MALIK)

ABSTRACT

Present energy use is largely dependent on fossil fuels which make future sustainable development very difficult. There are drastic changes in the composition and behaviors of our atmosphere due to the rapid release of polluting combustion products from fossil fuels. A significant amount of the carbon dioxide emissions from the energy sector is related to the use of fossil fuels for electricity generation. As the demand for electricity is growing rapidly, emissions of carbon dioxide and other pollutants from this sector can be expected to increase unless other alternatives are made available. Further, the declining energy supplies and severe environmental constraints compel us to sharply focus our attention on the need for additional amounts of clean energy sources.

Among the energy sources that can substitute fossil fuels, biomass fuels appear as the option with the highest general worldwide potential. In both the developed and the developing countries, the interest and activity for obtaining energy from biomass has expanded tremendously and dramatically in the last few years. There are large quantities of residues, associated with agricultural production and processing industries and they can be used for energy production, provided that they satisfy the criteria of plentiful supply and local availability on a renewable and perpetual basis.

Partial combustion of biomass in the gasifier generates producer gas that can be used for heating purposes and as supplementary or sole fuel in internal combustion engines. In this study the potential of various agricultural wastes (residues) as the feed stock for gasifier is analyzed. The agricultural residue used is cotton stalks.

The performance and emission parameters of the gasifier engine system are analyzed by running the engine for different cotton stalks particle size distribution and at different load conditions. The capacity of the gasifier is 10 kW. The system is experimentally optimized with respect to maximum diesel savings in the dual fuel mode operation while using the cotton stalks as biomass. The performance and emission parameters of the dual fuel engine are compared with that of diesel engine at different load conditions.

In the dual fuel mode of operation the diesel consumption reduced to 50% in dual fuel when producer gas from cotton stalks is used with diesel in comparison to diesel only. Nitrous oxide level is 20% lower in the dual mode as compared to diesel fuel mode of running. The smoke emission from the dual fuel mode of operation is 22% lower than that when diesel alone is used under all load conditions and also reduction in noise level of 4.5%

was observed in dual fuel mode. The economic analysis of the system shows the fruitful result for the investment made on this system. The internal rate of return was 29.37%. Also the cost of operation was 138.47 INR per hour for dual fuel engine whereas for diesel it comes out to be 230.00 INR per hour. And the cost of electricity generation in dual fuel mode is 14.34 INR per kWh. With reduction of 60% GHG emissions, the gasifier operated dual fuel diesel engine is economically feasible option for power generation.

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NOMENCLATURE

ASTM	American Society for Testing and Materials
ATDC	After Top Dead Centre
BMEP	Brake Mean Effective Pressure
BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
BTDC	Bottom Top Dead Centre
BTE	Brake Thermal Efficiency
CH ₄	Methane
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
DI	Direct Injection
EGT	Exhaust Gas Temperature
GC	Gas Chromatography
H ₂	Hydrogen
HP	Horse Power
IC	Internal Combustion
ISO	International standard organization
kW	Kilo Watt
LPG	Liquid Petroleum Gas
NA	Naturally Aspirated
NO _x	Oxides of Nitrogen
O ₂	Oxygen Level
SO	Smoke Opacity
SO ₂	Sulphur dioxide
TDC	Top Dead Centre
UHC	Unburned Hydrocarbon

Units

%	Percentage
kJ/kg	Kilojoule per Kilogram
kJ/kWhr	Kilojoule per Kilowatt hour

kPa	Kilopascal
MJ/kg	Mega joule per Kilogram
MPa	Megapascal
°C	Degree Celsius
ppm	Parts per Million
Vol	Volume

CHAPTER 1

INTRODUCTION

Any environmental action in this universe, whether done by humans or by nature is provoked due to the energy flow in any form! The primary infrastructure input required for economic prosperity and development of a country is energy. Before the industrial revolution people were essentially dependent on manual and animal labour but as the revolution take place the new electrical age started by the invention or introduction of electrical machines along with commercial availability electrical power. All this lead to an increase of energy required by leaps and bounds. For the continuous growth of human civilization energy is the life blood. As India in the 21st century with a population of 1.2 billion, the requirement of producing enough energy and applying engineering for greater infrastructure development glare in her face. The morning of the millennium compels us to look forward and gear ourselves to clear the inventory of development and meet future challenges.

1.1 ENERGY TREND IN INDIA

Our conventional energy sources such as coal, petroleum etc. are depleting at a high pace. In the year 2000, 62.3% of India's primary energy production is based on coal and petroleum contribution is 17.6%, hydroelectricity 9.9%, natural gas 9.2% and nuclear power 1% whereas in the year 2016, India's electricity is generated overwhelmingly by coal (61.5%), natural gas 8.2 percent, petroleum accounted for 0.3 percent, hydroelectricity 14 percent and nuclear and renewable energy which accounts for the balance 16 percent.

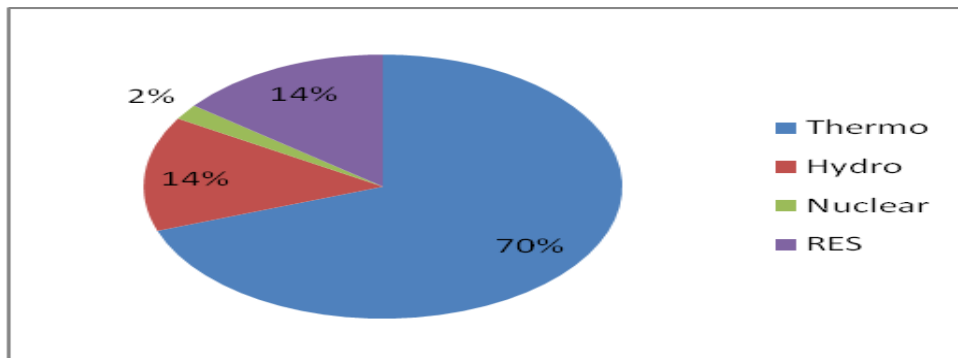


Fig. 1.1: Power generations installed capacity (2016) [70]

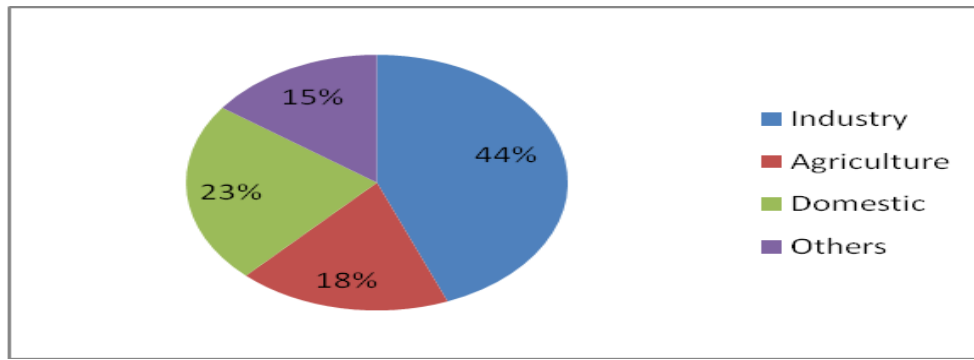


Fig 1.2: Sector wise energy consumption in India [31]

India will maintain to struggle an energy supply gap through the projected years. Since 1985 this shortfall has been worsening when the country starts importing of coal. In India oil demand rises 10 percent per year which dents the foreign exchange amount.

Table 1.1: Energy planning as per 5 years plans [40, 70]

5 Years Plan	Demand (MW)	Installed Capacity (MW)	Shortage (MW)
6 th (1980-85)	52,000	47,000	5000
7 th (1985-90)	75,000	65,000	10,000
8 th (1990-92,92-97)	1,05,000	85,000	20,000
9 th (1997-2002)	1,32,000	1,05,045	26,955
10 th (2002-007)	1,46,000	1,32,329	13,671
11 th (2007-012)	2,12,200	1,99,877	12,323
12 th (2012-017)	3,18,413	3,05,554	12,859

India's rapidly flourishing economy will run energy demand growth at a projected annual rate of 6.4% through 2016. This is the highest incremental energy demand rate of any major country in the world. The existing fuel requirement is likely to transform vaguely through the projected duration ending in 2016. Coal (sixty five percent) is expected to stay nearly the same as in 2000 whereas hydropower (fourteen percent) and natural gas (ten percent) will have advanced shares of total generation.

Table 1.2: Status of conventional sources of energy in India [28]

Coal	Consumption	355 MT
	Reserves	2, 80, 000 MT
Crude Oil	Consumption	106.6 MT
	Indigenous Production	32 MT
	Imports	74.6 MT
	Crude Proven Reserves	750 MT
Natural Gas	Consumption	29.9 MCM
	Reserves	740 BCM

Increasing demand of energy and depletion of available conventional sources from earth has drawn the attention of our scientists, engineers and technologists to develop various materials, devices and systems to harness non conventional energy sources. But there is also a major reason which compels us towards the non conventional energy sources. There are drastic changes in the composition in addition to behaviour of our environment due to the accelerated liberation of polluting emissions from fossil fuels. A compelling amount of the carbon dioxide emissions is correlated to the great use of fossil fuels for power production. Emission of carbon dioxide and additional pollutants from electricity generation can be predicted to extend as the requirement for electricity is rising till the further alternatives are made accessible. The additional sources of power that can reinstate fossil fuels are solar, wind, ocean and biomass. Apart from being pollution free, these are infinite and are freely available everywhere.

As of March 2015, Punjab's installed capacity of renewable energy consists of solar power (200 MW), biomass power (63 MW), small hydro (135 MW), waste to energy (1 MW), and cogeneration power (410 MW). Punjab has also set an objective of raising the percentage of renewable energy in the total energy requirement to 15% by 2022. It targets an installed capacity of 5,400 MW renewable capacities by 2022 which includes 300 MW from biomass, 680 MW from co-generation, 4,200 MW from solar, 200 MW from small hydro and 20 MW from waste to energy. Punjab has large solar and biomass potential as shown in Table 1.3

Table1.3: Renewable energy potential in Punjab [39, 42, 45]

Energy Sources	Country Potential (MW)	State Potential (MW)	State Exploited Potential(MW)
Solar	100000	2810 MW	200
Small Hydro	5000	441 MW	157.4
Biomass	19500	3172 MW	63
Cogeneration	3500	500 MW	362.59
Waste to Energy	3000	45 MW	1
Wind energy	45000	NA	NA

In case of solar energy the commercial prospects of larger thermal power plants one uncertain due to high cost per kW of installed capacity, low operating hours per day, larger ground area requirement etc. Wind energy though it is a cheap energy generation source, it may not be always available at all the places only heavy wind zones and a few places in medium wind zone provide economic sites for wind energy production. Ocean energy can also be generated at few locations. Therefore energy scenario is changing rapidly and dramatically in favour of biomass.

1.2 BIOMASS POTENTIAL

All raw materials which are volatile in character, mainly plant and living thing present in earth and water environments are biomass. Biomass includes remains of harvested agriculture products and processing industries such as straw, leaves, bark, cutting vines etc., in adding together to animal debris and plant goods used in agro-industrial processing such as grains, flour and some exceptional commodities such as cassava, seaweeds etc [50, 62, 63, 79].

It is the type of solar power stored in the elemental structure of the plant is amongst the most admired and most capable non conventional fuel, not only for energy production but also for industrial and household utilization in world. It provides not just foodstuff for the living but also power, building resources, paper, fabrics, medicines and chemicals. Ever since man discovered fire biomass has been used for the purpose of energy.



Fig 1.3: Natural biocycle [44]

Also, biomass absorbs the same quantity of carbon dioxide in flourishing itself that it releases when burned as a fuel in any form. It means that its contributions in worldwide warming are nil. Biomass fuels include the insignificant quantity of sulphur, so their contribution to acid rain is much minimized. Natural processes in the earth take millions of years in converting the organic matter into today's fossil fuels whereas, biomass comes from organic matter in trees, agricultural crops and other living material of plants. CO₂ from the environment and moisture from the soil are mixed in the photosynthetic method with the help of solar power to generate carbohydrates that are stored in the chemical bonds of the structural components of biomass. If the combustion of biomass is efficient, O₂ from the environment and carbon in plants after oxidization produces carbon dioxide and water. This process is cyclic because the CO₂ is then accessible to produce new biomass.

Utilization of biomass for power generation is a regular way to organize biomass waste materials or else it would create ecological hazards. India produces about 620 million tonnes of agricultural residues per year. Deposits generated by variety of crops were grouped into four categories based on the type of crop that is cereals, oilseeds, fibres and sugarcane.

Table 1.4: Total availability of crop residues in India [46]

Crop	Annual production	Dry residue generated	Residue to crop	Dry matter
	Mt/yr			
Rice paddy	153.35	192.82	1.5	0.86
Wheat	80.68	120.7	1.7	0.88
Maize	19.73	26.75	1.5	0.88
Jute	18.32	31.51	2.15	0.8
Cotton	37.86	90.86	3	0.8
Groundnut	7.17	11.44	2	0.8
Sugarcane	285.03	107.5	0.4	0.88
Rapeseed and Mustard	7.2	17.28	3	0.8
Millets	18.62	21.57	1.5	0.88
Total	627.96	620.43		

Large variation in crop remains generated across the various states of India depends on the crops sown in the states, their cropping concentration, and productivity. Cereal crop residues generation was maximum in the states of Uttar Pradesh (72 Mt) followed by Punjab (45.6 Mt). Uttar Pradesh contributed most to the residue generated from sugarcane (44.2 Mt) while fibre crop residue was leading in Gujarat (28.6 Mt) followed by West Bengal (24.4 Mt). Rajasthan and Gujarat generated about 9.26 and 5.1 Mt residues respectively from oilseed crops.

It is anticipated that about 300 million tonnes of residues are disposed of by blazing them in the open agricultural fields and creating ecological hazards. Every year Govt. of India issues the stringent laws to avoid the burning of these residue wastes in open field but those laws or warnings are not taken care off. These agricultural wastes can be successfully utilized by converting them into a gaseous flammable fuel termed as "Syngas" in suitably designed reactors (Biomass Gasifiers).

80% of the world's fundamental energy consumption is contributed by fossil fuel, 6% by nuclear energy sources and 14% by renewable (out of which biomass contributes 9.5%) as per World Energy Assessment report published in 2000 (Rogner and Popescu 2000). At present, biomass contributes fifteen percent of the overall energy supply globally and forty percent of this energy is consumed in emergent countries, mostly in rural areas. As against the potential for 19500 MW of biomass power, a capacity of 1000 MW has been commissioned till March 31, 2016 in India.

Table1.5: Crop wise residue generated in various states of India [46]

States	Crop residue generated (Mt/yr)			
	Cereal crops	Fiber crops	Oilseed crops	Sugarcane
Andhra Pradesh	33.07	16.07	2.5	5.8
Arunanchal Pradesh	0.56	0	0.06	0.01
Assam	8.15	2.01	0.29	0.41
Bihar	19.87	3.27	0.2	1.87
Chhattisgarh	8.87	0.01	0.11	0.01
Goa	0.24	0	0.01	0.02
Gujarat	8.18	28.62	5.06	5.85
Haryana	24.73	7.58	2.15	1.93
Himachal Pradesh	1.95	0	0.01	0.02
Jammu and Kashmir	2.76	0	0.11	0
Jharkhand	7.34	0	0.09	0.13
Karnataka	11.73	3.55	0.81	8.8
Kerala	1.14	0.01	0	0.1
Madhya Pradesh	16.05	3.51	2.13	1.12
Maharashtra	8.75	19.51	0.57	22.87
Manipur	0.78	0	0	0.01
Meghalaya	0.44	0.13	0.01	0
Mizoram	0.1	0	0	0.01
Nagaland	0.89	0.01	0.06	0.07
Orissa	13.38	0.56	0.16	0.24
Punjab	45.58	9.32	0.08	1.76
Rajasthan	22.19	2.96	9.26	0.15
Sikkim	0.14	0	0.01	0
Tamil Nadu	11.69	0.78	1.56	12.37
Tripura	1.22	0.02	0	0.02
Uttar Pradesh	72.02	0.04	2.49	41.13
Uttarakhand	2.4	0	0.03	2.11
West Bengal	37.26	24.43	0.95	0.62
A and N Islands	0.04	0	0	0
D and N Haveli	0.05	0	0	0
Delhi	0.17	0	0	0
Daman and Diu	0.01	0	0	0
Pondicherry	0.1	0	0	0.06
All India	361.85	122.37	28.72	107.5

1.3 BIOMASS UTILIZATION TECHNOLOGIES

Useful energy from biomass can be utilized by adopting following technologies:

- Direct Combustion
- Biomass Gasification
- Anaerobic Digestion
- Ethanol Production

1.3.1 Direct Combustion

Combustion is the basic practice for converting biomass into serviceable energy. Direct biomass burning has been a resource of energy for accomplishment of human needs from the starting of civilization. Following are the major feedstock utilized in this mechanism:

- Timber
- Agricultural residues
- Community solid waste

Heat and steam are the output produced from this process. From the scientific point of view it is a complex process. Proper designed industrial biomass combustors can burn all type of biomass fuel. Volatile hydrocarbons (C_xH_y) are burned in a hot combustion zone in this process. Combustion mechanics convert biomass fuels into different forms of useful energy for commercial as well as industrial uses. In a furnace, the biomass fuel converted into heat energy. The heat energy is released in the form of hot gases to heat exchanger that harness the thermal energy from the hot gases to the process medium (steam, hot water or hot air).

Direct combustion systems are either fixed bed or fluidized bed systems. Fixed-bed systems are basically distinguished by types of grates and the way the biomass fuel is supplied to or transported through the furnace. In a stationary or travelling grate combustor, a manual or automatic feeder distributes the fuel onto a grate, where the fuel burns. Combustion air enters from below the grate. In the stationary grate design, ash falls into a pit for collection. In contrast, a travelling grate system has a moving grate that drops the ash into a hopper.

Fluidized-Bed Combustors (FBC) burn biomass fuel in a hot bed of granular, noncombustible material, such as sand, limestone, or other. Injection of air into the bed creates turbulence resembling a boiling liquid. The turbulence distributes and suspends the fuel. This design increases heat transfer and allows for operating temperatures below 970°C , reducing NO_x emissions. Depending on the air velocity, a bubbling fluidised bed or circulating fluidised bed

is created. The most important advantages (comparing to fixed bed systems) of fluidized-bed combustion system are:

- Flexibility to changes in biomass fuel properties sizes and shapes;
- Acceptance of biomass fuel moisture content up to 60%;
- Can handle high-ash fuels and agricultural biomass residue (>50%);
- Compact construction with high heat exchange and reaction rates;
- Low NO_x emissions;
- Low excess air factor, below 1.2 to 1.4, resulting in low heat losses from flue gas.

Two cycles are possible for combining electric power generation with process steam production. Steam can be used in the process first and then re-routed through a steam turbine to generate electric power. This arrangement is called a bottoming cycle. In the alternate cycle, steam from the boiler passes first through a steam turbine to produce electric power. The back-pressure (or extracted) steam from the steam turbine is then used for processes or for heating (or cooling) purposes. This arrangement is called a topping cycle, which is the more common cycle.

1.3.2 Biomass Gasification

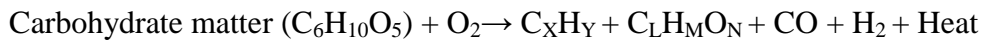
Gasification, production of combustible gas from carbon containing materials, is already an old technology. The first record of its commercial application origins from so called dry distillation (or pyrolysis – heating of feedstock on absence of O₂, resulting in thermal decomposition of fuel into volatile gases and solid carbon) origins from year 1812 (Gas Company in London). The first attempt to use producer gas to fire the internal combustion engine was carried out in 1881. Biomass gasification was reintroduced during the 2nd World War as the consequence of unavailability of petroleum. After the end of the war gasifier systems were substituted with engines driven by liquid fossil fuels again. It was not before the 1970s energy crisis when gasification came back for the third time through its history.

Biomass gasification is other thermo chemical conversion process utilizing the following major feedstock:

- Wood
- Agricultural waste
- Municipal solid waste

Chemical process of gasification means the thermal decomposition of hydrocarbons from biomass in a reducing (oxygen-deficient) atmosphere. The process usually takes place at about 850°C. Because the injected air prevents the ash from melting, steam injection is not always required. A biomass gasifier can operate under atmospheric pressure or elevated pressure. The resulting gas product, the synthetic gas, contains combustible gases – hydrogen (H₂) and carbon monoxide (CO) as the main constituents; by-products are liquids and tars, charcoal and mineral matter (ash or slag).

In general, the gasifying agent can be air, oxygen (O₂) or oxygen-enriched air. For biomass gasification, air is normally used as oxidant (oxygen as the oxidant agent is preferred in high capacity fossil fuel gasification systems). The net product of air gasification can be found by summing up the partial reactions, as follows:



The biggest advantage of gasification is the variety of feed stocks as well as products. The produced synthetic gas can be utilized not only as the fuel for power generation but also as the feedstock for chemical industry.

1.3.3 Anaerobic Digestion – Biogas

As per records, Alessandro Volta first discovered biogas in 1776 and Humphrey Davy was the first to pronounce the presence of combustible gas Methane in the Farmyard Manure in as early as 1800.

Anaerobic digestion is a biological process that produces a gas principally composed of methane (CH₄) and carbon dioxide (CO₂), known as biogas. The biogas is produced from the following major organic wastes:

- Solid and liquid animal manure
- Agricultural plant waste
- Waste from agricultural products processing industry
- Organic components in town waste
- Waste waters
- Landfills

Anaerobic digestion can be used to produce valuable energy from waste streams of natural materials or to lower the pollution potential of a waste stream. Biogas plant has a self-consumption of energy to keep the sludge warm. This is typically 20% of the energy

production for a well-designed biogas plant. Anaerobic digestion is a complex biochemical reaction carried out in a number of steps by several types of microorganisms that require little or no oxygen to live.

During the process a biogas, principally composed of approximately 65% methane (CH_4) and about 30% carbon dioxide (CO_2), is produced. The amount of biogas produced varies with the amount of organic waste fed to the digester and temperature influences the rate of decomposition.

Several different types of bacteria work in stages together, to break down complex organic wastes, resulting in the production of biogas. Controlled anaerobic digestion requires an airtight chamber, called a digester. A mixture of CH_4 with CO_2 is making up more than 90% of the total biogas composition. The remaining gases are usually smaller amounts of H_2S , N_2 , H_2 , methylmercaptans and O_2 . 0.55 kg of diesel oil is as good as biogas of 65% CH_4 content. After drying and filtering process, biogas is suitable as fuel for the heating as well as in internal combustion engine.

Biogas plants produce methane by anaerobic digestion. Today out of the total expected 960 million tonnes of cattle muck generated in the nation, over 35% is cooked in the shape of cattle muck cakes. If all this could be transformed to biogas and compost, the nation's supply of natural compost will augment by 112 tonnes. If the 35 % of cattle muck, which is burnt, as muck cakes are transformed into gas it will supply 12 million m^3 of gas which is sufficient for 28 million families.

But if the entire 980 million tonnes of dung is put through the gas plant it may provide 36000 million m^3 of gas enough for the kitchen of 87 million families. The human waste can also be used for producing biogas. Community latrines can be planned in the villages for collection of night soil for feeding to biogas plants. Waste of 200 persons can be used produce about 5 m^3 of gas per day to produce 12 kWh of equivalent energy by running a biogas engine. An additional resource of biogas is concealed in organic waste and community sewage. Sludge digestion produces biogas containing between 60-70% of CH_4 , with an average energy content of about 22 MJ/m^3 .

1.3.4 Ethanol Production

Starch content of Biomass feed stocks like corn, potatoes, beets, sugarcane, wheat, barley, and similar can be converted by fermentation process into alcohol (ethanol). Fermentation is the biochemical process that converts sugars into ethanol (alcohol). In contrast to biogas production, fermentation takes place in the presence of air and is, therefore, a process of aerobic digestion.

Ethanol producers use specific types of enzymes to convert starch crops such as corn, wheat and barley to fermentable sugars. Some crops, such as sugar cane and sugar beets, naturally contain fermentable sugars. Hydrolysis is the technology, which Converts Cellulose to alcohol's through fermentation. Ethyl alcohol can be produced from a Variety of sugars by fermentation with years. Molasses is diluted with water to a sugar content of about 20% by weigh acidified to pH 4.5 and then mixed with yeast culture in a fermentor. Ammonia is used to reduce acidity. When 8-10 percent alcohol is accumulated, then liquid is distilled, fractionated and rectified 2.5 liters of cane molasses produces about one liter of alcohol.

Ethanol is easier to transport and store than hydrogen, fuel reforming (using a chemical process to extract hydrogen from fuel) may be a practical way to provide hydrogen to fuel cells in vehicles or for remote stationary applications. Latin America, dominated by Brazil, is the world's largest production region of bio-ethanol. As the value of bio-ethanol is increasingly being recognized, more and more policies to support development and implementation of ethanol as a fuel are being introduced.

1.4 ADVANTAGES OF GASIFICATION

Among all the alternatives of technology used, gasification is the best suitable alternative in view of the following: -

1. Gasification offers high flexibility in terms of various biomass materials as feedstock.
2. Gasification has thermo-chemical conversion efficiencies in the range of 70% to 90%, which is highest among various alternative.
3. Gasification output capacity, especially in the high output ranges, is controlled only by availability of adequate feed materials rather than technical consideration.
4. The area requirement for gasification equipment is lowest per unit output of energy in the form of heat and/or electricity.
5. The gasification equipment has high turn down ratios comparable to biogas and higher than steam turbine systems.

1.5. GASIFIERS

The production of generator gas (producer gas) by gasification is partial combustion of solid fuel (biomass) which takes place at temperature of about 1000⁰C. The reactor is called a gasifier. The combustion products from complete combustion of biomass generally contain nitrogen, water vapor, carbon dioxide and surplus of oxygen. However in gasification where there is a surplus of solid fuel (incomplete combustion) the products of combustion are combustible gases like Carbon monoxide (CO), Hydrogen (H₂) and traces of Methane and non useful products like tar and dust. The important parameter in gasifier design is to create conditions such that a) biomass is reduced to charcoal and, b) charcoal is converted to CO and H₂ at suitable temperature.

1.5.1 Types of Gasifiers

Basically gasifiers are classified as fixed bed and fluidized bed type gasifiers similar to fixed bed or fluidized-bed systems in combustion technology. The significant differences concerned with these gasifiers are listed in Table 1.6[36] from which we selected the fixed bed gasifier for our work as it will fulfil our requirements very closely. Since there is an interaction of air or oxygen and biomass in the gasifier, they are classified according to the way air or oxygen is introduced in it. There are two types of gasifiers' downdraft and updraft. These are also called counter current and cocurrent respectively. These are also called countercurrent and cocurrent respectively.

Table 1.6: Significant differences between fixed bed and fluidized bed [36]

Fixed bed	Fluidized bed
(-) Higher investment (about 10%), two lines	(+) Lower investment
(-) Feedstock fines must be agglomerated	(+) No problems with feedstock fines
(-) Particle size as uniform as possible	(+) Broad particle size distribution
(+) Very great Particle size Possible (upto 100 mm)	(-) Limited Particle size (up to 50 mm)
(+) Nearly tar free gas	(-) Tar (1 g/m ³ n); high tar content in the gas
(+) High carbon conversion rate (90- 99%)	(-) Low carbon conversion rate (90%)
(+) Discharge of liquid slag	(-) Ash fusion by low-softening ash

Updraft gasifier has air transient during the biomass from base and the flammable gases come out from the peak of the gasifier whereas in the downdraft gasifier the air is passed from

the tuyers in the downdraft path. With minor variations almost all the gasifiers come in the above said categories. The biomass fuel and its size, moisture content and ash content, dictates the choice of one type of gasifier over the other.

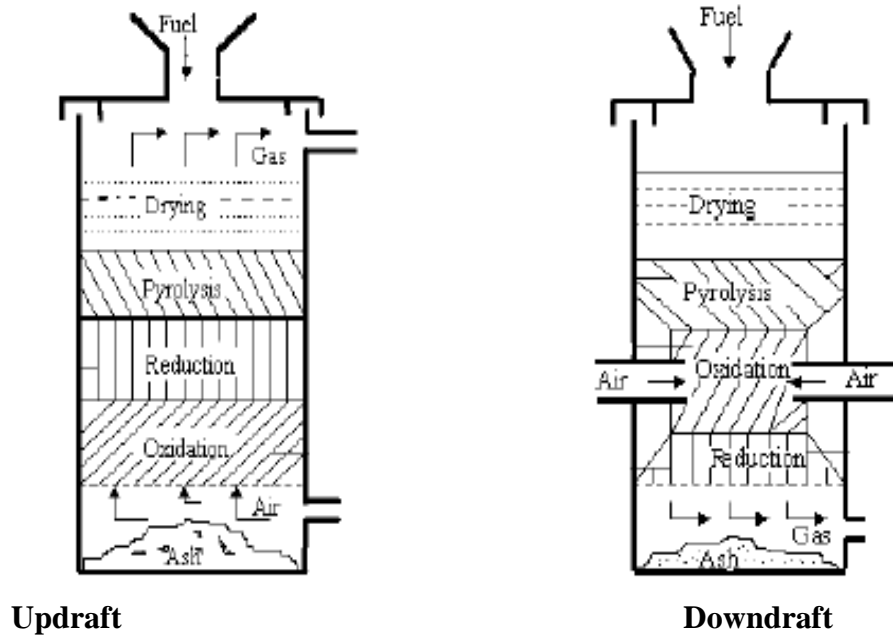


Fig 1.4: Updraft and Downdraft gasifiers

Table 1.7: Advantages and disadvantages of various gasifiers [29]

Sr. No.	Gasifier Type	Advantage	Disadvantages
1.	Updraft	<ul style="list-style-type: none"> -Small pressure drop -good thermal efficiency -little tendency towards of slag formation 	<ul style="list-style-type: none"> -Great sensitivity to tar and moisture and moisture content of fuel -relatively long time required for start up of IC engine -poor reaction capability with heavy gas load
2.	Downdraft	<ul style="list-style-type: none"> -Flexible adaptation of gas Production to load - Low sensitivity to charcoal dust and tar content of fuel 	<ul style="list-style-type: none"> -Design tends to be tall -not feasible for very small Particle size of fuel.
3.	Cross draft	<ul style="list-style-type: none"> -Short design height -very fast response time to load -flexible gas production 	<ul style="list-style-type: none"> -Very high sensitivity to slag formation -high Pressure drop

1.6 PROCESS ZONES IN GASIFIER

Four distinct processes take place in a gasifier as the fuel makes its way to gasification. They are:

- a) Drying of fuel
- b) Combustion
- c) Pyrolysis – a process in which tar and other volatiles are driven off
- d) Reduction

There is a considerable overlap of the above said processes, each can be assumed to occupy a separate zone where different chemical and thermal reactions take place. In the downdraft gasifiers there are two types:

- a) Single throat
- b) Double throat

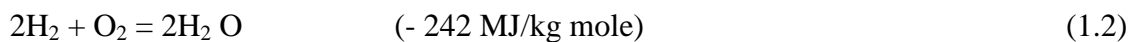
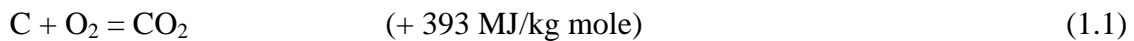
Single throat gasifiers are mainly used for stationary applications whereas double throat are for varying loads as well as automotive purposes.

1.7 REACTION CHEMISTRY

The following major reactions take place in combustion and reduction zone [14, 62, and 63]

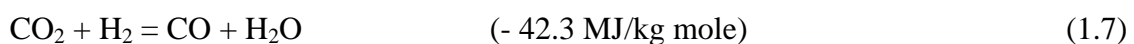
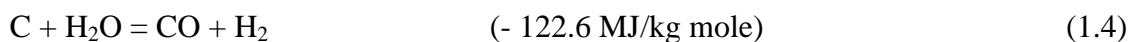
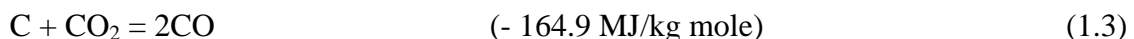
1.7.1. Combustion Zone

The combustible substance of a solid fuel is composed of elements carbon, hydrogen and oxygen. In complete combustion carbon dioxide is obtained from carbon in fuel and water is obtained from the hydrogen in the form of steam. The combustion reaction is exothermic and yields a theoretical oxidation temperature of 1450° C. The main reactions, therefore, are:



1.7.2 Reduction Zone

The products of partial combustion pass through a red-hot charcoal bed where the following reduction reactions take place.



Reactions (3) and (4) are main reduction reactions and being endothermic have the capability of reducing gas temperature. Consequently the temperatures in the reduction zone are normally 800-1000° C. Lower the reduction zone temperature (700-800° C), lower is the calorific value of gas.

1.7.3 Pyrolysis Zone

It is a complicated process to understand the whole mechanism. Temperature, pressure, contact time and heat loss has significant effect on the product of this process. The products of this process depended on temperature, pressure, in house time and warm up losses. Water from the process is driven off by 200° C and then CO₂ & CH₃COOH are come out between 200 to 280° C. The actual process takes place between 280 to 500° C, producing tar and gases. Some amount of CH₃OH is also produced in this process. After 500° C, hydrogen is produced in this process in small amount.

More tar formation takes place in updraft gasifier as compared to downdraft. Tar in downdraft gasifier is broken down as it has to pass the combustion and reduction zones temperature. In downdraft gasifier the tars have to pass during the combustion and reduction zone which make it busted. Finally in the drying zone the main process is of drying of biomass. Biomass entering the gasifier has moisture content of 10-30%. Some acids formation is also there which results into the corrosion of gasifier.

1.8 PROPERTIES OF PRODUCER GAS

The producer gas is affected by various processes as mentioned above so variations in the gas produced from various biomass sources are expected. Table 1.8 lists the composition of gas produced from various sources. The gas composition is also depending on gasifier design and thus, the same fuel may give different calorific value as when used in two different gasifiers. Almost 50-60% of gas is composed of non-combustible nitrogen. Thus it may be beneficial to use oxygen instead of air for gasification. When the end product is methanol – a high energy quality item, then the cost and use of oxygen can be justified. On an average 1 kg of biomass produces about 2.5 m³ of producer gas at S.T.P. In this process it consumes about 1.5 m³ of air for combustion. For complete combustion of wood about 4.5 m³ of air is required. The average energy conversion efficiency of wood gasifiers is about 60-70% and is defined as

$$\eta_{\text{GAS}} = \frac{\text{Calorific value of gas/kg of fuel}}{\text{Avg. Calorific value of 1 kg of fuel}} \quad (1.8)$$

Table 1.8: Composition of producer gas from various fuels [20, 29, 65]

Fuel	Gasification method	Volume Percentage					Calorific value MJ/m ³
		CO	H ₂	CH ₄	CO ₂	N ₂	
Charcoal	Downdraft	28-31	5-10	1-2	1-2	55-60	4.60-5.65
Wood	Downdraft	17-22	16-20	2-3	10-15	55-50	5.00-5.86
Wheat straw	Downdraft	14-17	17-19	-	11-14	-	4.50
Coconut husks	Downdraft	16-20	17-19	-	10-15	-	5.80
Coconut shells	Downdraft	19-24	10-15	-	11-15	-	7.20
Pressed Sugarcane	Downdraft	15-18	15-18	-	12-14	-	5.30
Charcoal	Updraft	30	19.7	-	3.6	46	5.98
Corn cobs	Downdraft	18.6	16.5	6.4	-	-	6.29
Rice hulls Pellet	Downdraft	16.1	9.6	0.95	-	-	3.25
Cotton stalks	Downdraft	15.7	11.7	3.4	-	-	4.32

1.9 TEMPERATURE OF GAS

On an average the temperature of gas leaving the gasifier is about 300 to 400° C. If the temperature is higher than 500° C then it is an indication that partial combustion of gas is taking place. This particularly happens when the air flow rate through the gasifier is higher than the design value.

1.10 GASIFIER FUEL CHARACTERISTICS

The real test for a good gasifier is not whether a combustible gas can be generated by burning a biomass fuel with 20-40% stoichiometric air but that a reliable producer gas can be made which can also be economically attractive to the customer. Towards this objective the fuel characteristics have to be evaluated and fuel processing is to be done.

A gasifier fuel can be classified as good or bad according to the following parameters:

- Energy content and Bulk density of the fuel
- Water content
- Dirt content
- Pitch content

- Slag and Ash characteristics
- Biomass type

1.10.1 Energy Content and Bulk Density of Fuel

The superior the energy content and bulk density of fuel, the analogous is the gasifier capacity since for one charge one can get power for prolongs time [20, 60].

1.10.2 Water Content

In most fuels there is very little choice in moisture content since it is determined by the type of fuel, its origin and treatment. It is desirable to use fuel with low moisture content because heat loss due to its evaporation before gasification is considerable and the heat budget of the gasification reaction is impaired. Besides impairing the gasifier heat budget, high moisture content also puts load on cooling and filtering equipment by increasing the pressure drop across these units because of condensing liquid. Thus in order to reduce the moisture content of fuel some pre-treatment of fuel is required. Generally desirable moisture content for fuel should be less than 20%.

1.10.3 Dirt Content

All gasifier fuels produce dirt which is a trouble as it can choke the internal combustion engine and hence it has to be separated. The gasifier design should be such that it should not generate other than 2-6 g/m³ of dirt [51]. The higher the dirt created, supplementary load is put on filters necessitating their repeated flushing and augmented maintenance [83, 114].

1.10.4 Tar/Pitch Content

Tar is one of the most unpleasant constituents of the gas as it tends to deposit in the carburetor and intake valves causing sticking and troublesome operations. It is a product of highly irreversible process taking place in the pyrolysis zone. The physical property of tar depends upon temperature and heat rate and the appearance ranges from brown and watery (60% water) to black and highly viscous (7% water). There are approximately 200 chemical constituents that have been identified in tar so far. A well-designed gasifier should put out less than 1 g/m³ of tar [83, 114].

1.10.5 Slag and Ash Characteristics

The powder residue left in the fuel behind absolute combustion is known as ash. Composition and amount of ash in a fuel have a major impact on the working of the gasifier. It affects the gasification method in two ways:

- It forms slag after fusion and hinder the descending run of biomass feed.
- It lowers the fuel's response to reaction by sheltering the points in fuel where ignition is initiated.

Ash and tar removal are the two most important processes in gasification system for trouble free operation. Some fuels with high ash content can be easily gasified if perfect ash removal system is installed in the gasifier. Only charcoal and wood have been thoroughly tested and proven to be reliable. The European nations had formulated sophisticated mechanisms of ensuring stringent quality rules on these fuels. Charcoal for the reason of being tar free and low ash content character was the favourable fuel during World War II and still remains so. Charcoal was mainly formed from timber and in the translation of timber to charcoal about 50% of novel energy was vanished. With the present energy crisis where most countries do not have enough supply of wood, agricultural residues are the advantageous and attractive option to use [89].

1.10.5 Biomass Type

Producer gas composition depends on the biomass elemental content. Producer gas production is highly reliant on H_2/C fraction as well as O_2/C fraction. It increases when these fraction augment, particularly with an increase in H_2/C fraction. An elevated O_2 concentration in biomass needs lower ER for gasification. [70]

1.11 PRESENT WORK

To meet the energy demand in decentralized manner and to contain emission of green house gases, among the different alternate energy sources, biomass is found to be viable and economical. However, utilization of biomass requires effective energy conversion processes and gasification is observed to be more effective for use of its end product (producer gas). Gasification is achieved in a gasifier. In the present work, a downdraft gasifier is connected to the VCR diesel engine for and it was running at dual fuel mode using cotton stalks as gasifier fuel. The objective is focused on the performance and emission of engine with cost effective downdraft gasifier system to obtain electrical energy in decentralized manner. Experimental investigations are carried out on a 5.0 kW for power generation application. The efficacy of present system is studied in terms of producer gas calorific value; equivalence ratio and particle size distribution with addition to performance and emission analysis with dual fuel running.

1.12 ORGANIZATION OF THE THESIS

Many a researchers have done substantial amount of work on the utilization of biomass in downdraft gasifiers for production producer gas and its subsequent use in engines, extensive literature review is carried out in order to identify the scope of the work. The literature review is presented in Chapter 2. A gap in literature with problem formulation is presented in Chapter 3. Methodology and equipment employed for the present research work is described in Chapter 4 as Experimental programme. Trends obtained from the experimental investigations are discussed and elaborated in Chapter 5 under the heading Results and discussion. Conclusions from the present research work are presented at the end as Chapter 6. Few recommendations are also presented for further research as use of biomass is expanding. References are given at the end.

1.13 SUMMARY

The current chapter addresses the importance of biomass as energy source, types of fuels, different biomass-energy conversion processes are also presented to focus on the biomass gasification process. A special attention is paid on types of gasifier, motivation for the present research work as well as the outline of the thesis.

CHAPTER 2

LITERATURE REVIEW

In this chapter, some of the important research papers related to dual fuel engine performance and emissions are reviewed under various operating conditions. In addition to that effect of biomass composition and economics related with biomass are also reviewed.

2.1 DUAL FUEL ENGINES PERFORMANCE

Dual-fuel operation is found to be one of the attractive ways of conserving precious conventional fuels like diesel and petrol. In the dual fuel mode of operation, two fuels would be used, normally a gaseous fuel and a liquid fuel. Immense work is being done to assess the performance of dual-fuel engines. In this section, some of important papers related to dual-fuel operation are presented.

Vyarawalla et al (1984) have designed and developed a 9 kW biomass-based gasifier engine system for power generation and pumping of water applications. It was suggested that 75% diesel substitution in CI engines by syngas from the gasifier is easily achieved during its 1000 hours trial. Also, with the use of the producer-gas unusual wear & tear and maintenance problems of the engine are not foreseen from the field trials.

Mendis et al (1989) summarise the gasifier monitoring study results on 19 parameters installed at Burundi, Seychelles, Vanuatu in the South Pacific and Mali. They mentioned that gasifiers work in good health in the ground level, but should be customized as per the requirements of feedstock as compared to the desires of the energy demand. The discarding of polluted waste water is a regular crisis in developing countries, as appropriate expertise being available in developed countries to utilise the waste streams safe. In brief, they concluded that the inconvenience no longer lie with the technology of gasification but are now connected with its execution.

Rajwanshi and Joshi (1989) presented and evaluated the functioning experiences of powering a 3.75 kW diesel pump set by a topless hybrid gasifier and its financial investigation. They mentioned that regular diesel substitution varied from 51-76% depending on the load applied on an engine and it will diminish as the load is improved. To produce 1 kWh of motorized power for pumping water the gasifier requires 1.33 kg of timber and 125 ml of diesel.

Shashikantha et al (1994) developed a 15kWe spark ignition producer gas engine by converting a 17kWe direct injection diesel engine. They had been modified the design of combustion chamber geometry i.e. bowl-in-piston (hemispherical) was modified to Hesselman (shallow W) with an aim of achieving a higher level of turbulence by squish rather than swirl. The compressions ratio reduction from 16 to 11, an introduction of the ignition system and air gas mixture mountings are the other major modifications done for their study. They concluded that engine efficiency of 28-32 % is achieved at a static ignition timing of 35° BTDC with wood based producer gas of 6-7 MJ/Nm calorific values. Krishna & Kumar (1994) worked on coffee husk as biomass feedstock for gasification to analyse the performance of diesel engine in twin fuel mode. The maximum diesel substitution of 31% only was reported in their work. They recommended that this is due to clinkers development and a low density of biomass.

Martin et al (1997) studied the gasification of wood from the mill, which is integrated with a combined cycle for power production, as well as with the fuel synthesis. This combination makes better use of the gasifier, since the synthesised gas can be used to generate excess electricity during the winter season when electricity prices are high, whereas it can be used to produce transportation fuels at other times. The study shows that by using surplus waste wood from a pulp mill can generate fuel grade dimethyl ether to replace over 20000 litres of diesel fuel per day while maintaining electricity self-sufficiency. They also suggested that using the waste wood in an integrated gasification combined cycle gives 35 % higher power efficiency as compared to the conventional bark fired boiler and steam turbine.

Sridhar et al (2001) addressed the misconception associated with the use of producer gas as a reciprocating engine fuel. Their experiments had shown that the engine runs smoothly at a compression ratio of 17: 1 without any auto-ignition problem. They have been conducted experiments on multi-cylinder spark ignition engine modified from a diesel engine at varying compression ratios from 11.5: 1 to 17: 1 with the same combustion chamber design. Maximum brake power of 17.5 kW_e was obtained at an overall efficiency of 21% in their study of experimentation. The maximum de-rating of power in gas mode was 16% as compared to the normal diesel mode of operation at comparable compression ratio, which is very low as compared to previously reported studies. The overall efficiency declined by 32.5% compared to a normal diesel engine.

Kishore et al (2004) studied the role and potential of biomass resources in developing countries for addressing concern of global climate change. It was mentioned that collection & processing of biomass, low-end use capability of conventional devices and the inability to prevail biomass energy technologies are major barriers for utilization of the available bio resources more efficiently in a regular way. Technological promotion of activities which use biomass more easily is a key strategy to integrate the concerns of developing and developed countries. They recommend utilization of a basket of energy technologies, rather than a single technology to distribute energy and economic services in rural areas. This was the key for successful commercialization and mainstreaming of biomass energy technologies. A vision of establishing and running a chain of rural energy service companies, operating with a basket of technologies, under the general provisions of Clean Development Mechanism was also recommended. Technical performance and sustainability of the largest biomass gasifier-based power plant (500 kW) in India have been reviewed with respect to diesel replacement, fuel wood supply, the cost of electricity generation and environmental pollution. The overall efficiency of that plant is about 19% and the diesel replacement obtained at the optimum load condition was 64% (**Sonaton et al 2004**).

Singh et al (2006) investigated the properties of cashew nut shell and its effect on gasification feasibility for open core down draft gasifier. The performance of gasifier was evaluated in terms of fuel consumption rate, the calorific value of producer gas and gasification efficiency at different gas flow rates. The trend in the cashew nut shell system performance was similar to wood and biomass briquettes with higher conversion rate. Volumetric percentage of all the combustible constituent, gas calorific value and gasification efficiency increased, in general, with the increase in gas flow rate. Gasification efficiency was maximum (70%) at a gas flow rate of 130 m³/h and specific gasification rate of 167 kg/m²h which was comparable to that of wood. It proved that cashew nut shells could successfully be used as feedstock for open core down draft gasifier.

Ramadhas et al (2006) investigated the prospective of coir-pith and wood chips as the biomass fuel for gasifier. They analysed the performance of the gasifier-engine test rig by running the engine for different producer gas ratios and at different load conditions.

It is reported that the higher capacity of the engine than the required capacity must be selected because the producer gas twin fuel engine could run only at a maximum of 50–60% of maximum load condition. The engine performance decreases with increase in emissions at part load conditions both at diesel and twin fuel mode of operation. At optimized conditions, the

exhaust emissions are found to be closer irrespective of the fuel used. In the twin fuel mode of operation, while using wood chips higher diesel savings is achieved when compared to coir pith. The diesel replacement while using coir pith in the gasifier could be improved by briquetting.

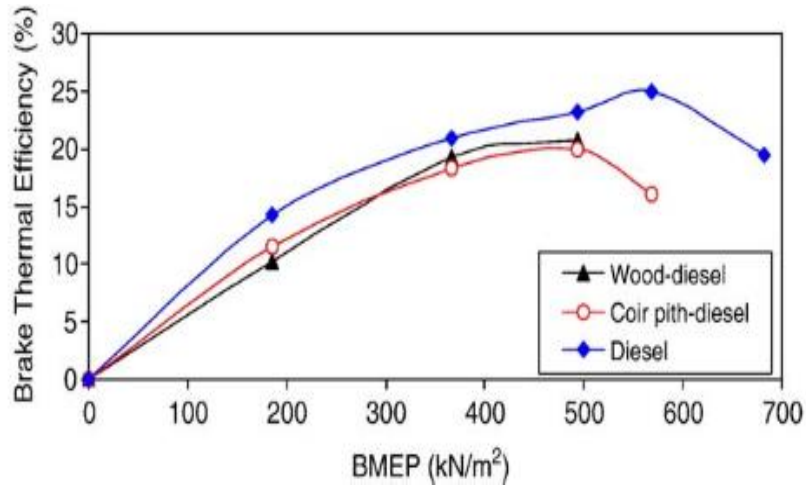


Fig.2.1: Brake thermal efficiency of the engine w.r.t. BMEP [82]

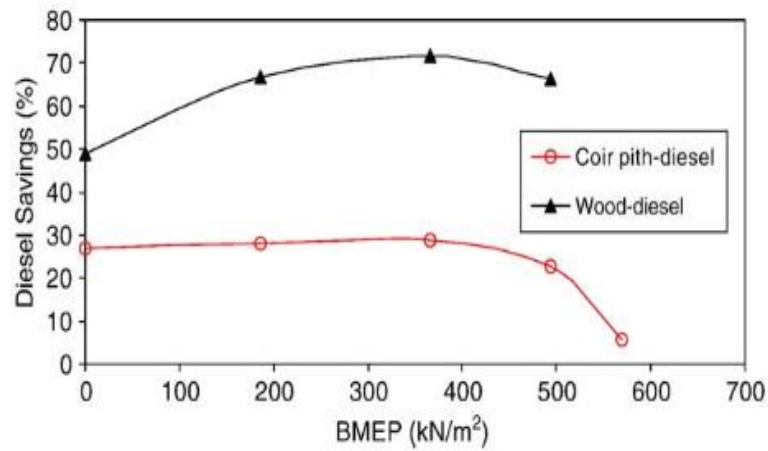


Fig.2.2: Diesel savings obtained in the dual fuel mode operation [82]

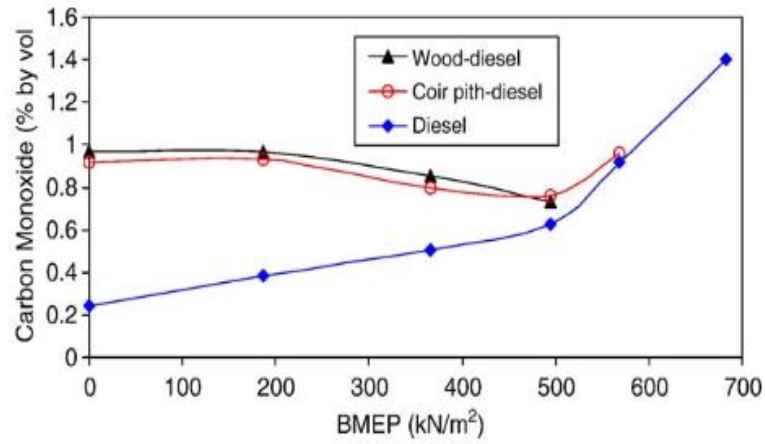


Fig. 2.3: Carbon monoxide emissions of the engine w.r.t. BMEP [82]

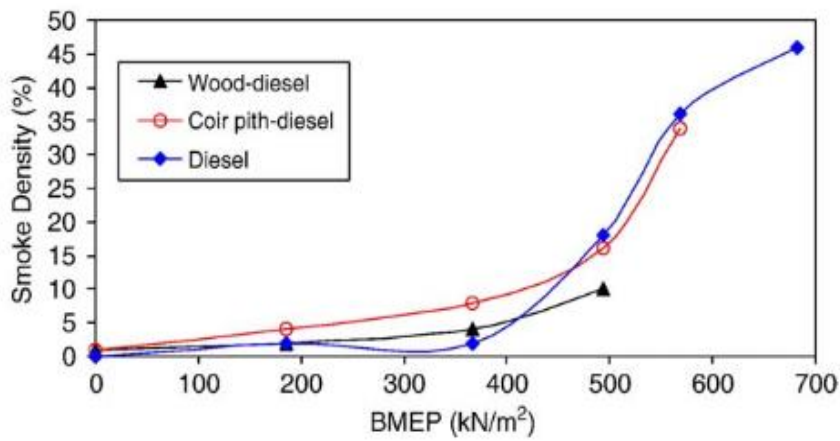


Fig.2.4: Smoke density of the engine w.r.t. BMEP [82]

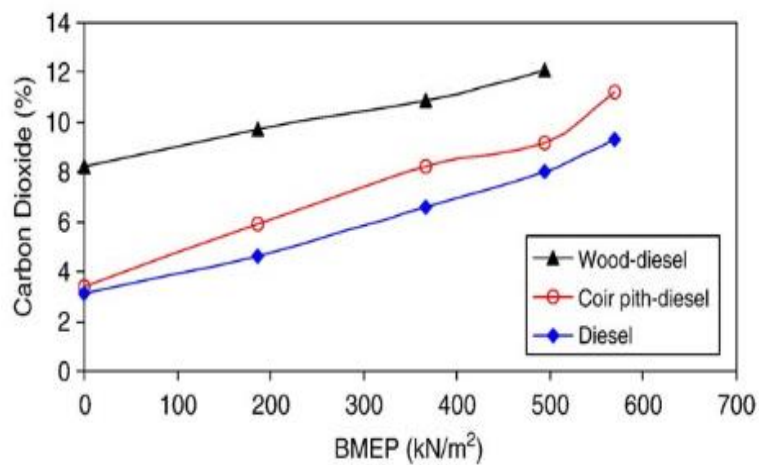


Fig.2.5: Carbon dioxide emissions of the engine w.r.t. [82]

Ramadhas et al (2008) analysed the twin fuel mode operation using coir-pith derived syngas and rubber seed oil as pilot fuel for different producer gas ratios and at variety of load conditions. The engine performance decreases in twin mode operation with diesel or rubber seed oil as pilot fuel. The pilot fuel consumption of rubber seed oil is higher than that of diesel in twin fuel mode operation. Carbon monoxide emission of rubber seed oil-producer gas operation is higher than diesel-producer gas operation under all load conditions because of higher fuel consumption with lower calorific value fuels. Moreover, higher carbon dioxide emissions are observed with rubber oil-producer gas operation. Also exhaust emissions were found to be closer irrespective of the fuel used.

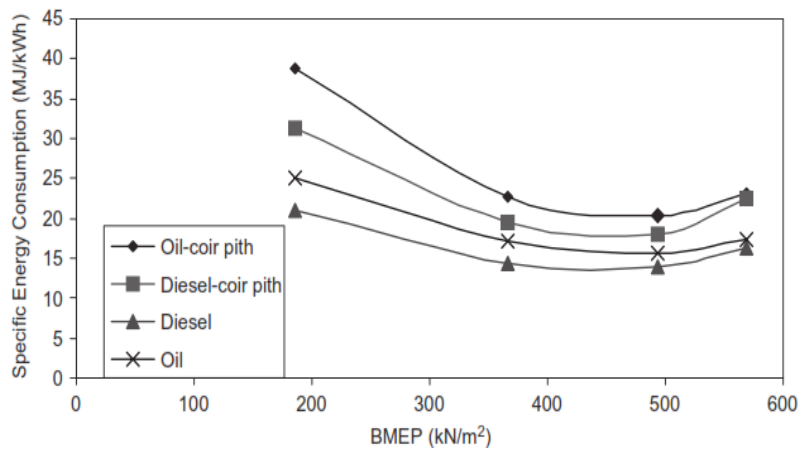


Fig.2.6: Specific energy consumption of engine with various fuels [83]

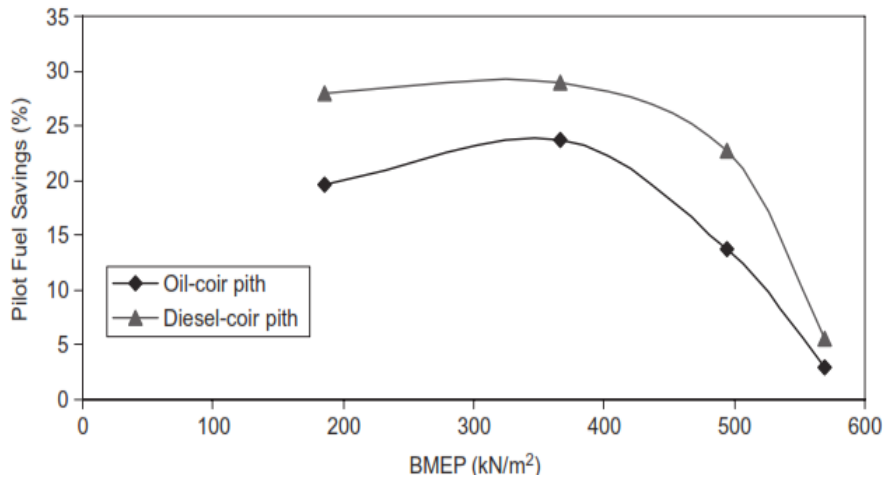


Fig.2.7: Pilot fuel savings of dual fuel engine [83]

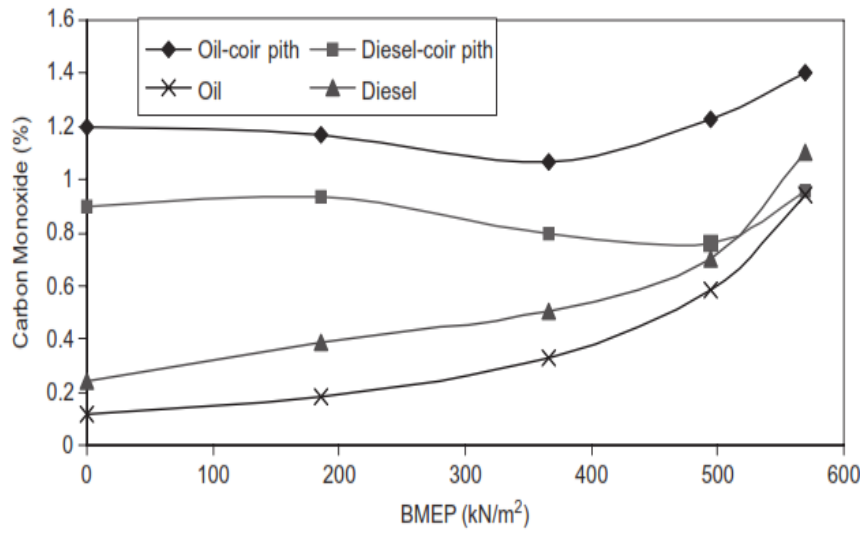


Fig.2.8: CO emissions of engine with various fuels [83]

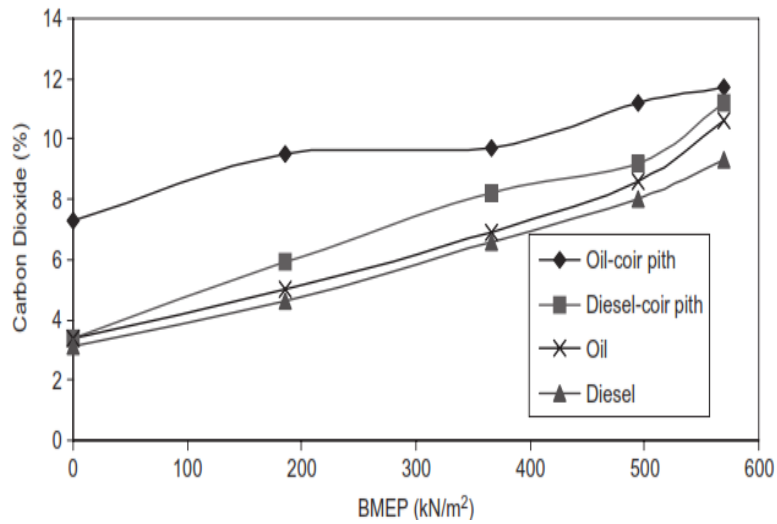


Fig.2.9: CO₂ emissions of engine with various fuels [83]

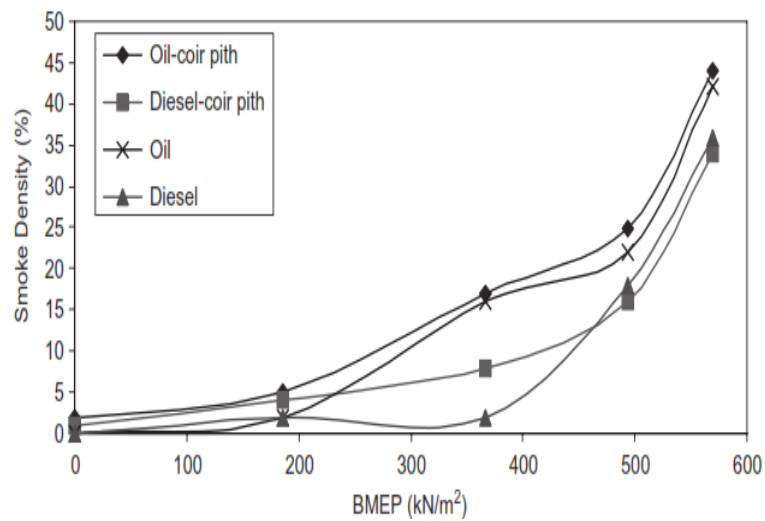


Fig.2.10: Smoke density of engine with various fuels [83]

Raman et al (2013) designed and developed a down draft gasifier based power generation system of 75 kW_e. They designed and installed a heat exchanger which recycles the heat of hot gas into the reactor which improves the efficiency of gasification production. A new ash removal system was installed in the system that minimises the rate of charcoal removal from the reactor which will increase the carbon conversation efficiency. A vibrating grate mechanism was introduced to remove the ash from the reactor, at a regular interval. The charcoal return to the ash pit was reduced by 83% due to this improvement. Also, hot air injection contributes to minimising the specific fuel (wood) consumption to 1.18 kg/kWh. Biomass to electric power conversion efficiency is found to be 18%. The cold gas efficiency of the system is increased from 75.0% to 88.4%. The energy conversion efficiency of producer gas to electric power was worked out to be 21%. Significant increase in the calorific value of the producer gas was also achieved by supplying hot air for gasification.

Dhole et al (2014) studied the effects of blends using hydrogen and producer gas with diesel on the performance and emissions characteristics of twin fuel engine. They have founded that blend of hydrogen and diesel in the ratio 20% : 80% respectively results in the 8% increase in the brake thermal efficiency where as blend of producer gas and diesel in the ratio 30% : 70% respectively results in the 7% decline in the BTE. The mixture of syngas and hydrogen in the fraction 60:40 with diesel in the fraction of 40:60 respectively as a fuel in twin fuel engine, total of 3% decline in the BTE was observed. There study concludes that the mixture hydrogen, producer gas and diesel have much better results for performance and emissions of twin fuel engine with respect to the blends of producer gas with diesel and hydrogen with diesel. NO_x emissions were reduced by using blends where as hydrocarbon emissions were increased by using blends. **Jain et al (2014)** presented the emission of air pollutants from biomass burning in India. They prepared a state-wise inventory of crop residue burnt in India and the air pollutants emitted. Punjab, Uttar Pradesh, Haryana and Maharashtra are the major states where the maximum amount of crop residues was burnt on the farm. Rice, wheat and sugarcane are the major crops whose residues are subjected to on-farm burning. Large scale burning of crop residues from rice, cotton & wheat in Punjab, Haryana and western Uttar Pradesh is a matter of serious concern not only for GHG emission but also for problems of pollution, loss of nutrients and health hazards. The residues are put to various productive usages and this is possible only if the residue is collected and managed properly.

Homdoun et al (2015) investigated the performance of a small diesel engine converted into a Spark Ignition engine running on 100% producer gas with high CR. The conventional swirl combustion chamber was replaced by a cavity chamber. The effect of variable compression

ratios from 9.7 to 17:1, engine speeds at 1000 and 2000 rpm and loads from 20% to 100% on engine performance were investigated in terms of engine torque, power output, thermal efficiency, specific fuel consumption and emissions. The modified SI engine was able to operate with producer gas successfully. Reduction in torque and power de-rating were observed for the producer gas engine mainly due to the low energy density of the air/fuel mixture and low volumetric efficiency of the engine. Increasing CR was shown to improve the brake thermal efficiency and the specific energy consumption slightly. The brake thermal efficiency was lower than the original diesel engine at 11.3%. Maximum brake power was observed to be 3.17 kW, and the best BSFC of 0.74 kg/kWh were achieved. Maximum brake thermal efficiency of 23.9% was obtained. The smoke density of the producer gas engine were 0–2%, while 1.5–12% for diesel engine during the tests.

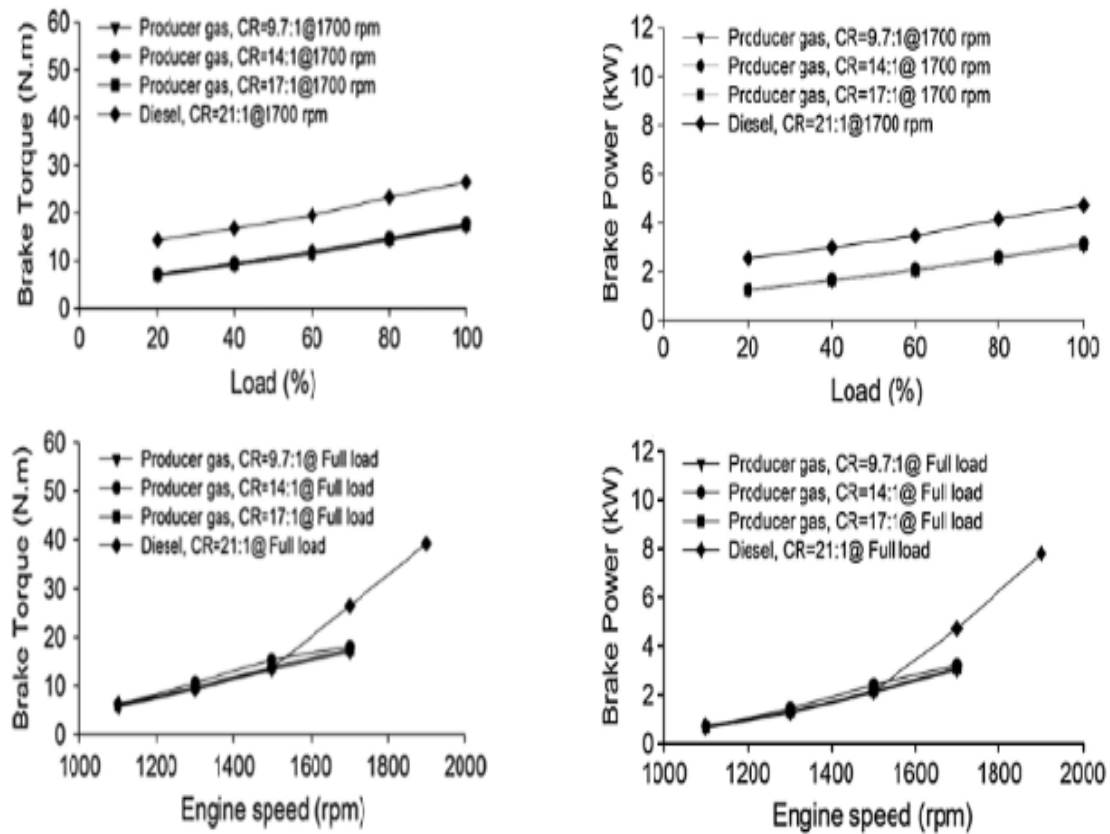


Fig. 2.11: Brake torque and Brake power w.r.t. Speed and Load [38]

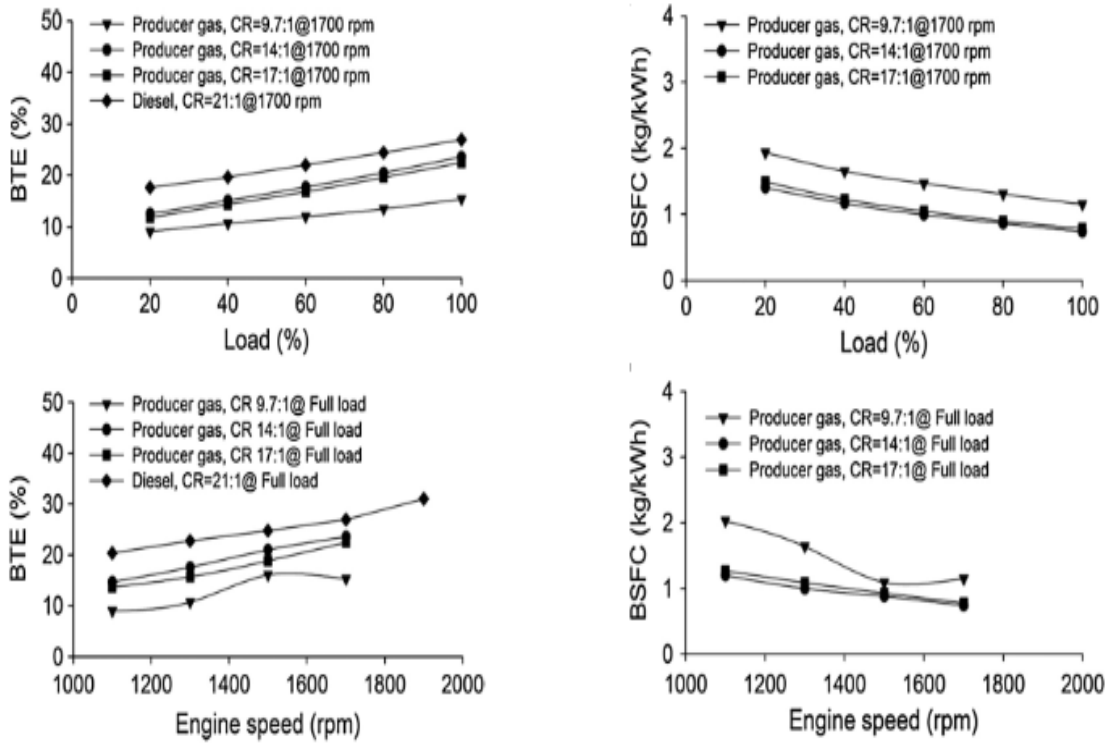


Fig.2.12: BTE and BSFC w.r.t. Speed and Load [38]

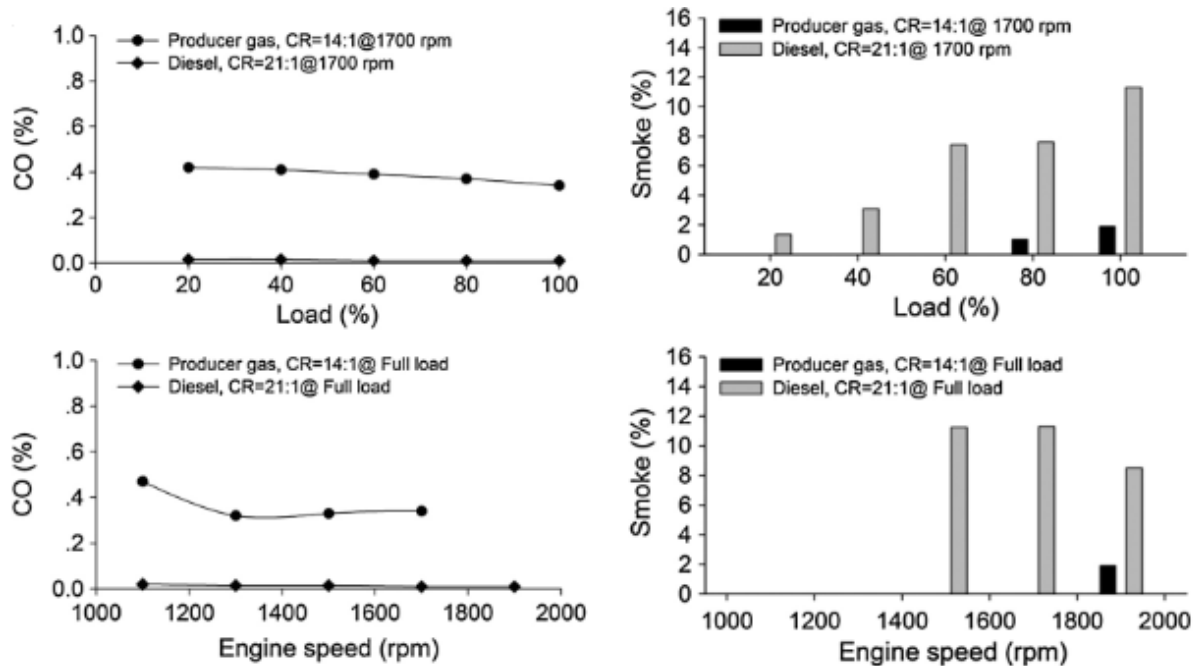


Fig.2.13: CO and Smoke Emissions w.r.t. Speed and Load [38]

2.2. DUAL FUEL ENGINES EMISSIONS

Immense work is being done to assess the emissions of dual-fuel engines. In this section, some of important papers related to dual-fuel emissions are presented.

Parikh et al (1989) have compared the performance of direct injected and indirect injected diesel engine running with producer gas from downdraft gasifier. Subaboolis used as a biomass sample in their study. By changing the volume of gas cooling – cleaning system they achieved the diesel replacement of 60-80% at 80 % of rated load. It has been established that twin fuel operation results in significant rise in engine exhaust CO content with a reduction in smoke level. Elevated drain temperature of twin-fuelled direct ignition engine was observed as compared to twin fuelled indirect ignition engine due to late burning. The advanced level of instability in the combustion chamber resulted in a more quick combustion of the air-fuel mixture in IDI engine. A high degree of instability is more appropriate for twin-fuel diesel engine design and operation. For achieving best system performance the requirement for application-specific alteration of the gasifier and the engine units by optimisation of the design of gas processing sub-system was also recommended.

Wu et al (2003) tested the performance analysis of a 1-MW biomass gasification based electric power generation system. Their experimental results indicate that operating temperature of the gasifier and ratios of air to fuel have a strong influence on gasifier performance characteristics like gasification efficiency, the conversion efficiency of carbon, gas productivity, gas composition, and its low heating value (LHV). They concluded that the optimal operation parameters for wood powder feed are temperature 780 °C, the equivalence ratio of 0.26, 70% gasification efficiency, 80% conversion efficiency of carbon, and LHV 5.8 MJ/m³. It was quoted by them that fly ash carried by fuel gas and tar produced during biomass gasification is the major factors affecting the continual operation of the electric power generation system. The loss of sensible heat due to fly ash leads to the low efficiency of electric power generation. The emission of SO₂ & NO_x of fuel gas from biomass gasification is below 20 ppm as compared to coal based power generation. The concentration of pollutants such as carbon monoxide(CO), oxides of nitrogen (NO_x), sulphur dioxide (SO₂), hydrocarbons (HC) and particulates in the flue gas was monitored and emission factors have been derived using kikar wood as biomass fuel in downdraft biomass gasifier clubbed with a twin fuel diesel engine. In addition to the emission characteristics, diesel replacement rate at different loads was estimated. The diesel engine is capable of running with twin fuelling with 67–86% diesel replacement rate. Also, engine performance decreases with increase in emissions at part load conditions both at diesel and twin fuel mode. For optimum load condition (80% of the rated capacity) the emissions were generally below the emission norms except for carbon monoxide emission from twin fuel operation, which exceeds the standard due to the combination of factors such as a low heating value of gas, low adiabatic flame temperatures, and low mean effective pressures. Carbon

monoxide emissions from twin fuel engines were higher than diesel engines at all operated load condition. Twin fuel operation reduces NO_x and SO_2 emission without increasing particulate emission (**Uma et al 2004**).

Sheth & Babu (2005 & 2009) studied the effect of water content on the composition and reaction rate. To carry out the study they developed a simulation model. Simulation tests are done by altering the water content (dry basis) ranging from 4wt% to 21 wt%. Following outcomes are derived from the study:

- Hydrogen percentage in gas is increasing with a linear increment of moisture content.
- Carbon monoxide percentage in gas is declining and carbon dioxide is escalating with an addition of water content.
- CH_4 concentration in syngas has no significant effect with moisture content increment.
- The composition of carbon dioxide is declining along the reduction bed up to the same height when carbon monoxide starts diminishing and later on carbon dioxide starts escalating.
- For 21 wt% water content, the percentage of CO is maximised up to the bed length of 0.21 m and the slightest diminution in CO percentage for the water content of 4 wt% is reported.

Babu et al (2006) studied variations in producer gas quality and rate of consumption of biomass fuel at different rates of air flow and by using biomass materials with different moisture content. The various parameters evaluated in the study are composition of producer gas, Calorific value of gas, cold efficiency of gasification process, various zone temperatures and equivalence ratio. The main conclusions reported in study are as follows:

- With increase in biomass moisture content, the rate of consumption of biomass decreases.
- Biomass consumption rate increases if rate of air flow is increased.
- Amount of CO_2 and N_2 in producer gas decline with raise in equivalence ratio till value of 0.205.
- If value of equivalence ratio is further increased from 0.205, fractions of CO start increasing.
- With change in equivalence ratio variation in ratios of H_2 and CO follows just reverse trends as compared with CO_2 and N_2 .
- Temperature of oxidation zone and pyrolysis zone are maximum at $\Phi = 0.205$.

- Calorific value is maximised at equivalence ratio of 0.25 and its value decreases for value of Φ between 0.205 to 0.35.
- Increase in Φ leads in increase in rate of production of gas.
- In case of downdraft gasifiers optimum value of equivalence ratio is reported as 0.205.

Banapurmath et al (2007) evaluated the feasibility of Honge oil/Honge oil methyl ester and producer gas as a total replacement for diesel fuels. Experimental tests have been conducted on a single cylinder four-stroke CI engine operated on single and dual fuel modes at three injection timings of 19°, 23° and 27° BTDC. The experimental results have shown that indicated brake thermal efficiency in dual fuel mode of operation to be lesser than single fuel mode of operation at all the injection timings. Also, it was mentioned that the brake thermal efficiency improved marginally when the injection timing was advanced for both Honge oil and Honge oil methyl ester. Brake thermal efficiency at injection timing of 27° BTDC are 24.25%, 22.25% and 23% were obtained with producer gas–diesel, producer gas–Honge oil and producer gas–Honge oil methyl ester, respectively. Smoke emission for producer gas–Honge oil was found to be more than producer gas–diesel oil. However, with producer gas–Honge oil methyl ester reduced emissions were obtained. With dual fuel operation, smoke and NO_x emissions were considerably reduced with an increase in CO emissions.

Singh et al (2005 & 2007) also investigated the effect of refined rice bran oil and producer gas with diesel on the emissions characteristics of a diesel engine generator set. In twin fuel mode (fossil diesel+ producer gas), the concentration of pollutants like carbon monoxide(CO), carbon dioxide (CO₂), nitric oxide (NO), nitrogen dioxide (NO₂) reduced by 55%, 19.7%, 82% and 83%, respectively, while hydrocarbon (HC) increased by 67.2% as compared to fossil diesel. Operated in twin fuel mode of (fossil diesel + refined rice bran oil), the concentration of pollutant like CO, CO₂, and HC reduced by 60%, 0.86% , and 91% respectively whereas NO increased by 23.48% as compared to fossil diesel. In mixed fuel mode (pre-heated blends of refined rice bran oil & fossil diesel in the proportion of 3:1 and producer gas) the concentration of pollutants like HC, NO and NO₂ reduced by 48.28%, 61.57% and 80.48%, respectively, while CO increased by 16.31% as compared to fossil diesel.

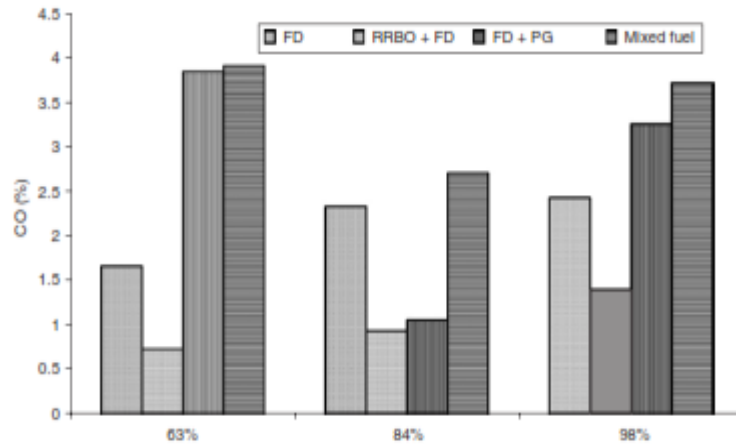


Fig.2.14: Effect of fuels and engine loads on CO [94, 95]

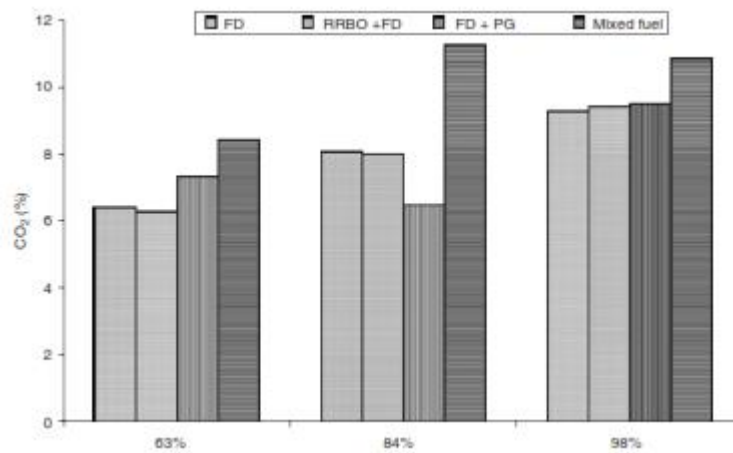


Fig.2.15: Effect of fuels and engine loads on CO₂ [94, 95]

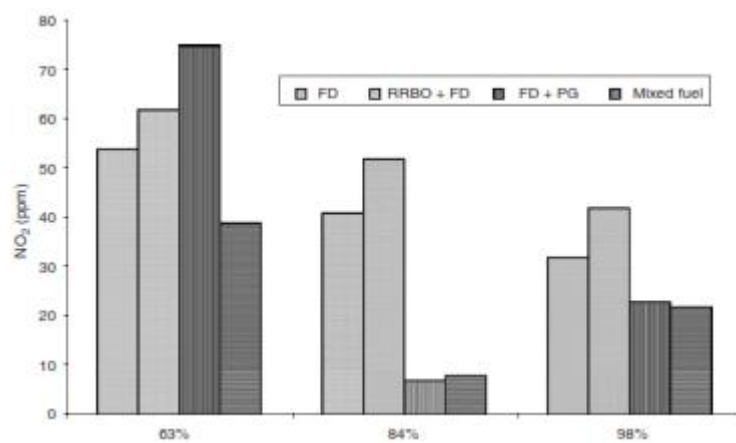


Fig.2.16: Effect of fuels and engine loads on NO₂ [94, 95]

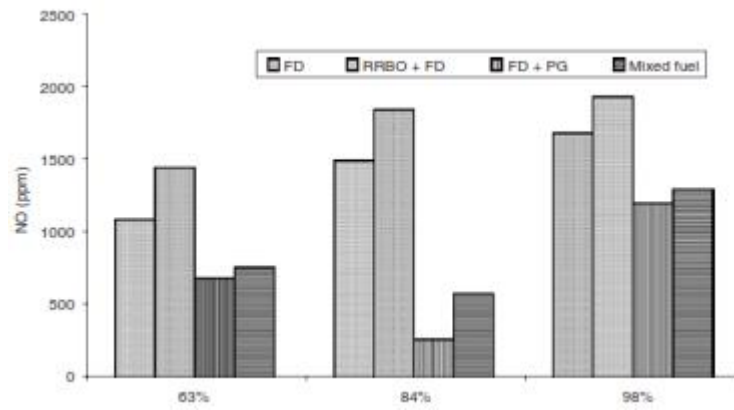


Fig.2.17: Effect of fuels and engine loads on NO [94, 95]

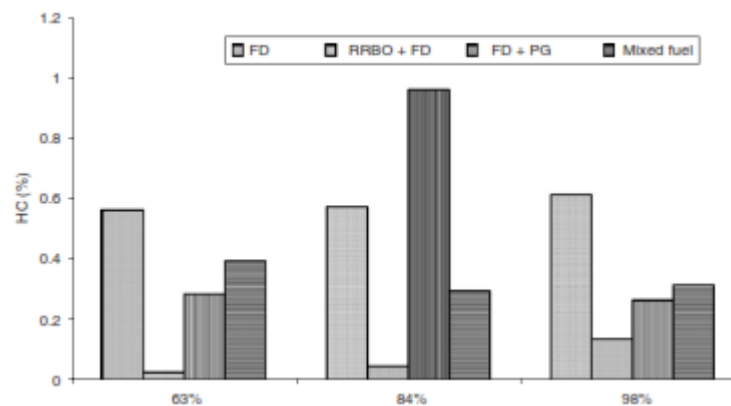


Fig.2.18: Effect of fuels and engine loads on HC [94, 95]

Panwar & Rathore (2007, 2009) studied a wood gas hob in solving cooking energy prerequisite by means of biomass gasification. The thermal effectiveness of the hob was 26.5% and it can be started, operated and closed with very low emissions. Also, it can employ a wide range of biomass fuels. The generated wood gas burns with a blue flame like liquid petroleum gas with a flame temperature of 736° C. The combustion effectiveness and heat-capture effectiveness of hobs are superior to efficiencies of open fires and hobs currently in use, favouring the need for less fuel. The stove has exhibited about 35% thermal efficiency with carbon monoxide and carbon dioxide emission were in the range of 3–6 ppm and 17–25 ppm respectively. The stove works in the power ranking of 1.53 to 1.76 kW.

Madlener & Bachhiesl (2007) studied the Austria's largest 65.7MW wood-fired cogeneration plant which was planned to operate in mid-2006. They focussed on the overall scientific and logistic perception, the project's past record, the main factors concerned, and significant socio-economic, institutional, and ecological aspects of the venture. From there study the following points are concluded:

- The existence of a crucial group of principal movers seems to be a vital prerequisite for the recognition of such a big and pioneering venture;
- A statement of objective by political parties in support of a sizable venture can overlay the techniques for the auxiliary expansion process;
- The reality of a crisis and crisis consciousness seems to assist the understanding of such large urban venture;
- If shareholder-owned companies are mixed up; then financial situations have to be encouraging.
- Institutional originality and changes in the state of mind of the core judgment makers;

2.3 BIOMASS COMPOSITION

Biomass composition plays a vital role in the gasification. The effect of biomass composition on producer gas generation and engine performance are presented in this section.

Hasler & Nussbaumer (1999) investigated the tar and particle collection efficiencies in a sand bed filter, a wash tower, two different fabric filters, and a rotational particle separator in different test runs with fixed bed gasifiers. The determined data was compared from catalytic tar crackers, venturi scrubbers, a rotational atomiser, and a wet electrostatic precipitator presented in the past literature. They concluded that for a successful application of biomass derived producer gas from small scale gasifiers is the tar removal, where further research & development is needed.

Drift et al (2001) studied the effect of moisture on the various characteristics of gas produced in ten different biomass fuels. They give the idea that more water content means superior amount of air is needed to sustain the process heat resulting in enhanced carbon alteration with lesser tar discharge but also inferior product gas calorific value and cold gas efficiency.

Hanaoka et al (2005) investigated the effect of woody biomass components on air-steam gasification using the downdraft fixed-bed gasifier at 1173 K and at atmospheric pressure. The gasification conversions in cellulose, xylem and lignin were 97.9%, 92.2%, and 52.8% on a carbon basis, respectively. The product gas composition in cellulose were 35.5 mol% CO, 27.0 mol% CO₂ and 28.7 mol% H₂ and the CO compositions were higher than the CO₂ or H₂ compositions, which is similar to that in the Japanese Oak, of which the main component was cellulose. In contrast, the product gas compositions in xylem and lignin were approximately 25

mol% CO, 36 mol% CO₂, and 32 mol% H₂, and the CO composition is lower than the CO₂ & H₂ compositions, which were similar to those in Japanese red pine bark, of which the main component was lignin. The fundamental information obtained in the gasification of each component could be used to predict the composition of product gas generated in air-steam gasification of different woody biomass.

Sheng & Azevedo (2005) reported the importance of the heating value of biomass fuels in designing and simulations tasks of biomass thermal conversions systems. Analysis of various methods available in the literature for estimating of heating values of fuels is done in depth. Generally, heating value is estimated on the basis of data acquired from chemical analysis, ultimate analysis or proximate analysis. In this study, statistical evaluation of all correlations is done on basis of large databases of samples of biomass fuels which are obtained from the literature. It is reported that correlations done on the basis of data obtained from the ultimate analysis are more accurate as compared to others and on the other hand correlations done on the basis of data obtained from proximate analysis have lower precision because only empirical biomass composition is provided by proximate analysis. Also, the correlations obtained on basis of biochemical compositions are not very accurate. The reason behind this is the variation observed in properties of components

Sagues et al (2007) proposed a fuzzy controller in biomass gasifiers. Information from the previous literature experts was formulated as fuzzy rules in order to increase the efficiency of the plant. Fuzzy logic includes an alternative way to design the controller using a higher level of absorption, more robust to dynamic conditions of the product load. Type of biomass and its moisture content level are imported to the controller by a human operator at the beginning of an operation to make it work separately. Satisfactory results were obtained which signifies the improved performance of the proposed control system as compared to conventional controllers utilising fixed parameters.

Patil et al (2007) studied the composition of cotton stalk plant. He noticed that stalk of cotton plant contains approximately 26% of lignin, 68% of cellulose and 7% ash. It is also observed that stalks of cotton resemble most types of wood available in fibre dimensions. This is not seen in case of other available agricultural wastes. So it is concluded that stalks of cotton have capability to generate producer gas which is rich in CO having high calorific value as compared with producer gas obtained from other agricultural wastes.

Vyas & Singh (2007) investigated the fuel properties of jatropha seed husk and its gasification feasibility in open core down draft gasifier. Performance is evaluated in terms of fuel consumption rate, calorific value of producer gas and gasification efficiency at different gas flow rates. Producer gas calorific value and concentration of CO, along with gasification efficiency, increased with the increase in gas flow rate. The maximum gasification efficiency is found to be 68.31% at a gas flow rate of 5.5 m³/h and specific gasification rate of 270 kg/ m²h which is comparable to that of wood

Kantarelis & Zabaniotou (2009) investigated the pyrolysis and fixed bed air gasification of cotton stalks. They had shown that pyrolysis produced a H₂ rich and CO reduced gas, favoured at high temperature. Syngas (CO and H₂) was the effective gas in the pyrolysis gaseous products, reaching a maximum concentration of 84% v/v at 760° C, while by gasification only 56% v/v achieved at 950° C and with $\lambda = 0.02$. Although, slightly lower conversion of biomass during pyrolysis was achieved (72 wt% at 760° C) comparing to gasification (75 wt% obtained at 950° C and $\lambda = 0.07$), produced gas had better quality in terms of syngas and CO₂.

Sahoo et al (2009) conducted a number of experiments to evaluate performance and emission characteristics of conventional diesel engine by running it on twin fuel mode using syngas. The main attraction of study is that no modification is done in existing diesel engine operating parameters and design to perform experiments. Different ratios of H₂ and CO are used to study influence on various engine emissions (HC, NO_x and CO) and performance parameters such as thermal efficiency, maximum cylinder pressure, exhaust gas temperature and diesel substitution. The diesel engine used is constant speed and four stroke in nature and uses direct injection fuel supply systems. Study is done at various loads conditions (20%, 40%, 60%, 80%, and 100%) and ratios of H₂ and CO in gas used for study are 50:50, 75:25 and 100:0. In this way, the influence of syngas fuels obtained from various sources and processing methods can be examined using this study.

Sivakumar & Mohan (2010) performed experiments using a downdraft gasifier. Three biomass materials are used for gasification processes which are rice husk, groundnut shell and coconut shell. Operating temperature of gasifier is kept as 800°C. The main findings of study are as follow:

- Coconut shells have 23% higher calorific value of syngas as compared to groundnut shell.
- The content of CO in coconut shell gas has 17% and 21 % higher than the gas from groundnut shell and rice husk.

- Ratio of hydrogen in producer gas is highest in case of ground nut shells.
- In case of gasification of coconut shells methane content in gas is 6.1% which is 38% higher as compared with other two.
- It is concluded that coconut shells are best compatible for gasification process as compared with other two biomass materials as they have comparatively high carbon content.

Chen et al (2010) propose a model of syngas production from municipal solid waste gasification with air in fixed bed reactors. The Aspen plus simulator model is used to predict the results of MSW gasification. The effects of gasification temperature, air equivalence ratio and moisture concentration on the composition of syngas, the lower heating value of syngas, heat conversion efficiency, and carbon conversion are investigated through this model. The results indicate that higher temperature improves gasification lower heating value, heat conversion efficiency, and carbon conversion. The effective temperature of should be 650 °C for the air equivalence ratio of 0.4. A high air equivalence ratio increased the carbon conversion while decreasing the lower heating value. Heat conversion efficiency increased and reached a maximum, then decreased while the ratio increased. The favourable air equivalence ratio should be 0.5 for the gasifier temperature of 600 °C. Higher moisture concentration increases the carbon conversion and increases the heat conversion efficiency at lower ratios. The maximum lower heating value of 5976 kJ/Nm³ at 600 °C was achieved at the moisture concentration of 30% while the maximum lower heating value (6598 kJ/Nm³) at 700 °C was achieved at 5%. Higher temperature and a lower equivalence ratio are favourable for obtaining a higher lower heating value of syngas at the same moisture concentration.

Son et al (2011) investigated the characteristics of syngas production from biomass gasification in a downdraft gasifier. The gasifier was combined with a small gas engine system for power generation. Syngas temperatures from the gasifier were maintained at a level of 700-1000 °C. For the air-fuel ratio of 0.3-0.35, the lower heating value of syngas was 1100-1200 kcalN/m³ and the cold gas efficiency of 69-72%. Tar concentration in raw syngas was around 3.9-4.4 gN/m³ which is very low as compared to tar generation volume of around 10-30% generated by the other type of fixed-bed gasifier as mentioned in the previous studies of literature. Syngas combustion in the gas engine showed that HC concentration was below 200 ppm, and NO_x concentration was below 40 ppm in the exhaust gas.

Martínez et al (2011) operated gasifier on air and mixture of steam and oxygen, to study effect on producer gas composition in two cases. He noticed calorific value of producer gas obtained from wood using air as oxidizing agent is low whereas when mixture of steam and oxygen are used to oxidize gasifier fuel, calorific value of generated gas is high. Main observations reported in study are as follow:

- Calorific value of produced gas in case of air ranges between 3-6 MJ/Nm³.
- Calorific value of produced gas in case of mixture of steam and oxygen rises to 18 MJ/Nm³.
- For gasification process of wood using a downdraft gasifier, characteristic yield values range between 2 and 3 Nm³/kg.
- Cold efficiency of the downdraft gasifier using wood ranges between 50% to 80%.
- Typical composition of produced gas when air is used as oxidizing agent is: 15-20% CO, 10-15% CO₂, 15-20% H₂, 0.5-2% of CH₄, and rest is O₂, N₂ and C_xH_y.

Bika et al (2011) studied the engine knocking and combustion features of a SI engine operating with altered hydrogen and carbon monoxide proportions. They have performed there study on single cylinder cooperative fuel research engine using three blends of syngas in which concentration of carbon monoxide and hydrogen vary by volume. Tests are conducted at three compression ratios of the range 6:1, 8:1, and 10:1, and three equivalence ratios of the range 0.6, 0.7, and 0.8. The knock limit in the compression ratio range of a hydrogen/carbon monoxide mixture increases with growing amount in carbon monoxide fraction, for a given fixed spark timing. For a given equivalence ratio and spark timing, of 50%/50% hydrogen/carbon mixture produced knock limited compression ratio of 8:1 as compared to 100% hydrogen condition, which produced knock limited compression ratio of 6:1. The burn period and ignition lag were also increased with increased in carbon monoxide fraction in the mixture. It was reported that although carbon monoxide was a slow burning fuel, higher carbon monoxide fractions in syngas can be beneficial, because of its increase in the confrontation to knock, which results that higher potential of producing carbon monoxide augmented the efficiencies of twin fuel spark engine.

Arunachalam & Olsen (2012) evaluated the knocking characteristics of five different compositions of producer gas. Variation in amounts of hydrogen and carbon dioxide in the producer gas composition on critical compression ratios were evaluated by experimental testing and simulation. It was observed that a 1% increase in CO₂ increased the compression

ratio by 0.32 units and a 1% increase in H_2 decreased the compression ratio by 0.14 units. The relative impact of CO_2 on theoretical compression ratio is over two times that of H_2 .

Arnavat et al (2013) studied the modelling of biomass gasification process using Artificial Neural Networks in fluidised bed gasifier. Two architectures of ANNs models are presented for circulating fluidized bed gasifiers and for bubbling fluidized bed gasifiers. They determine the producer gas composition (CO , CO_2 , inputlayer H_2 , CH_4) and gas yield. Previously published experimental data from literature has been used to train the ANNs. ANNs models use the biomass composition & few operating parameter input layer and two neurones in the hidden layer and then applying the back propagation algorithm. The results obtained by these ANNs show high agreement with published experimental data ($R^2 > 0.98$). Also, a sensitivity analysis has been applied in each ANN model showing that all studied input variables are important. This was the first of its kind study in this field where ANN is applied for modelling and analysis of a gasification system.

Jordan & Akay (2013) investigated the impact of granular calcium oxide on tar composition, concentration, dew point and syngas yield during gasification of bagasse. The use of 2, 3 and 6 wt. % in-bed calcium oxide promoted the conversion of Class1, 4 and 5 tar to Class 3 tar. This resulted in a decrease in tar yield ranging from 16 to 35%, a decrease in the tar concentration in syngas of 44–80%, an increase in syngas yield of 17–37%, and a decrease in tar dew point of 37–60 °C as the calcium oxide concentration was increased from 2 to 6 wt. %. 6 wt.% of the calcium oxide was found to be the most efficient in increasing syngas yield, reducing the tar concentration and decreasing the tar dew point in gasification.

Galindo et al (2014) presented an experimental evaluation of the quality of the producer gas in a two-stage, air supply downdraft gasifier. Experimental tests are performed by varying the operating conditions of the gasifier: the air flow between 18 Nm^3/h and 22 Nm^3/h and the air flow ratio in the two stages between 0% and 80%, evaluating the effects of these parameters over the quality of the gas. For a total air flow of 20 Nm^3/h and an air ratio between the two stages (AR) of 80%, the gasifier can produce a fuel gas with low tar and particles content from 54.25 to 102 and 4 mg/Nm^3 respectively compared to a tar and particles content of 418.95 and 146.03 mg/Nm^3 obtained for a total air flow of 20 Nm^3/h and an AR of 0%. These results confirm that the use of a second stage air supply enables a reduction of 87% in tar yield and of 29.9% in the particle content of the gas. The producer gas for this operational condition had a composition of 19.2 vol % of CO , 1.3 vol % of CH_4 , 17.14 vol % of H_2 , 14.22 vol % CO and

with an average LHV of 4.74 MJ/Nm^3 . These results are due to an increase of the temperatures in the pyrolysis and combustion regions.

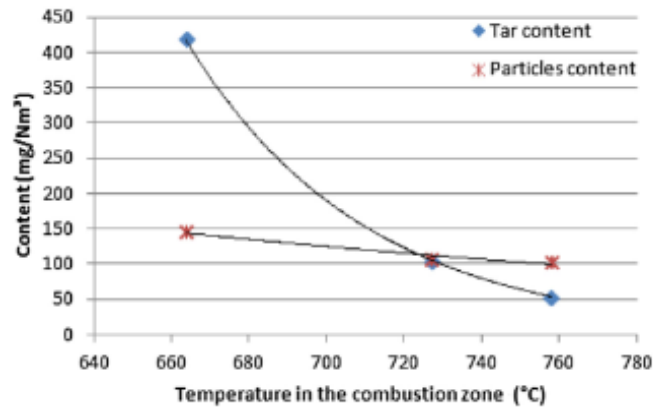


Fig.2.19: Effects of the temperature in the combustion zone on the tar and particle content in the producer gas [31]

Shivapuji & Dasappa (2014) studied the effect of bio-derived hydrogen and carbon monoxide rich syngas on the sensitivity of combustion phasing and combustion descriptors to ignition timing, load and mixture quality on fuelling a multi-cylinder natural gas engine. It was found that for producer gas, flammability limits were as 0.42-1.93, the optimal engine operation was at an equivalence ratio of 1.12. The general trends of the combustion descriptors for producer gas fuelled operation were similar to those of conventional fuels. Influence of H_2 fraction on the terminal and initial combustion phase and hence on the descriptor sensitivity to ignition have been quantified. Gasoline operation agreed strongly with the indicated conditions as compared to syngas. They suggested that above parameters have higher sensitivity with producer gas as compared to gasoline.

Prasad (2015) conducted a number of experiments to evaluate performance characteristics of conventional diesel engine by running it on twin fuel mode using syngas produced from jatropha shells. It has generated a very low calorific value producer gas. The gasification efficiency obtained was 64 % for jatropha shells which is very low and also there is lump formation in gasifier which makes the gasifier stop in producer gas production mechanism.

2.4 BIOMASS PARTICLE SIZE EFFECT

Ergudenle & Ghaly (1992) investigated the quality of gas composition produced from wheat straw. Its production rate at various equivalence ratios (0.35, 0.25, 0.20 & 0.17) and fluidization velocities (0.37, 0.33 & 0.28 m/s) using a 400 kW, fluidised bed gasifier of twin distributor type was studied. They concluded that gas composition was affected majorly by the

equivalence ratio. They also mentioned that the best quality of the gas, as per the mole fractions of the combustible components in gas and the higher heating value will be achieved at a maximum equivalence ratio of 0.25 and fluidization velocity of 0.28 m/s.

Table 2.1: Gas composition [28]

Fluidization Velocity (m/s)	Equivalence Ratio	Gas Composition(%) dry basis						
		CO ₂	CO	CH ₄	H ₂	N ₂	C ₂ H _n	O ₂
0.37	0.35	14.05	19.55	4.29	6.39	2.59	2.59	0.98
	0.25	13.6	19.65	4.59	7.41	2.56	2.56	1.74
	0.2	13.38	20.34	4.57	5.39	2.37	2.37	2.83
	0.17	17.75	19.78	4.6	4.85	2.19	2.19	0.79
0.33	0.35	13.56	16.26	3.36	5.12	2.13	2.13	1.83
	0.25	14.02	19.7	4.39	7.01	2.4	2.4	0.82
	0.2	14.86	21.84	4.59	4.44	2.35	2.35	1.58
	0.17	16.2	20.54	3.74	3.24	1.83	1.83	1.66
0.28	0.35	13.93	16.66	17.66	6.19	2.26	2.26	1.52
	0.25	13.77	23.35	23.35	6.8	3.11	3.11	0.2
	0.2	15.28	23.59	23.59	4.75	2.49	2.49	0.26
	0.17	16.11	22.92	22.92	4.05	2.11	2.11	0.24

Table 2.2: Gas flow rate, higher heating value [28]

Fluidization Velocity (m/s)	Equivalence Ratio	Normalized Gas Production (Nm ³ /kg fuel)	Higher Heating Value (MJ/kg fuel)
0.37	0.35	2.04	12.71
	0.25	1.63	10.56
	0.2	1.5	9.29
	0.17	1.26	7.54
0.33	0.35	2.11	10.7
	0.25	1.65	10.41
	0.2	1.43	8.95
	0.17	1.27	6.77
0.28	0.35	2.31	12.84
	0.25	1.76	12.83
	0.2	1.48	9.75
	0.17	1.23	7.422

Zainal et al (2002) studied the impact of equivalence ratio on the gas composition, calorific value and the gas production in downdraft biomass gasifier. They presented that the calorific value of the producer gas increases with equivalence ratio initially and after attaining a peak it will decrease with the increase in equivalence ratio. The gas flow rate per unit weight of the biomass increases linearly with equivalence ratio. It is also observed that complete conversion of carbon to gaseous fuel has not taken place even for the optimum equivalence ratio. Optimum equivalence ratio for the best performance of downdraft biomass gasifier comes out to be 0.38. The specific consumption of the biomass materials (furniture wood and wood chips) is found to be of the order of 2 kg/kWh, while the overall efficiency of the biomass electrical power producing system is of the order of 10–11% and the cold gas efficiency is of the order of about 80% under optimum equivalence ratio. Feed rate also effects on Calorific value/composition of the product gas and the associated variations of gasifier zone temperatures (**Dogru et al 2002**). Optimum operation of the gasifier was found to be between 1.44 and 1.47 Nm³/kg of air fuel ratios at the values of 4.06 and 4.48 kg/h of wet feed rate which gives the producer gas with a good gross calorific value of about 5 MJ/m³ at a volumetric flow of 8–9 N m³/h product gas. A gasifier has been fabricated in Sri Lanka for the tea industry. Experimental testing of the design under various conditions has produced data that has then been used to calibrate a computer program, developed to investigate the impact of design parameters and features of gasifier on conversion efficiency. It was concluded that a wood chip size of 3–5 cm with moisture content below 15% (dry basis) should be used in that gasifier. Feed material with a fixed carbon content of higher than 30% and heat losses of more than 15% should be avoided. For the above parameters, the gasification zone should be 33 cm long to achieve an acceptable conversion efficiency (**Jayah et al 2003**).

Tinaut et al (2008) used a downdraft gasifier to develop a one dimensional stationary model of gasification process of biomass. The basis of model development is equations of energy and mass conservation. The parameters like exchange of energy between gaseous and solid phases are also included in study. He also proposed the process of transfer of heat from the solid particles by radiation. Effect of various parameters like velocity of air flow, gasifying agent composition, gasifying agent's inlet temperature, type of biomass, biomass particle size, geometry of gasifier etc on the gasification process was studied using proposed model. It is reported gasifier system works with highest efficiency when small sized biomass particles are used and air flow velocity is kept lower.

Masmoudi et al (2014) developed and numerically solved a two dimensional steady state mathematical model for a downdraft gasifier. The model results showed a satisfactory agreement with the experimental data using an exponential variation for the bio-char reactivity factor and an effectiveness factor. Simulations have been carried out and it was presented that the loading of the gasification process is mainly affected by the temperature field and the reactivity of the char. The simulated distribution sand fields highlighted the kinetic and the transport phenomena occurring locally inside the gasification zone. The particle size was found to have a considerable effect on the hydrogen and carbon monoxide yield and distribution. The model is a useful simulation tool to study bio-char gasification by predicting the different fields inside the gasification zone and the gasifier performance in term of gas composition and the effect of the inlet boundary conditions.

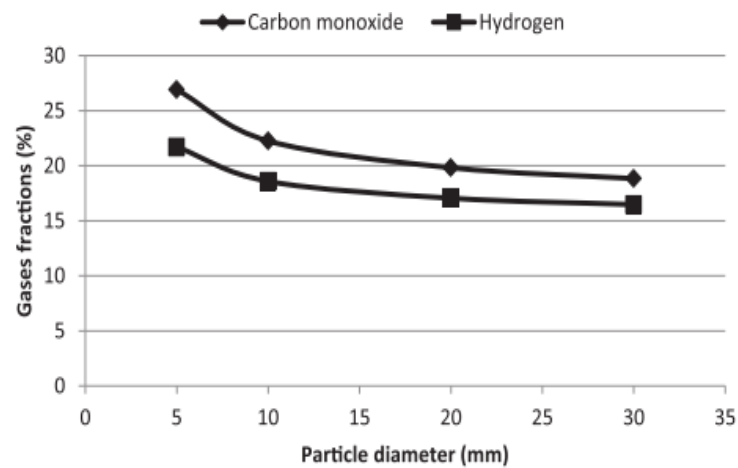


Fig.2.20: Effect of particles size on the produced gas fractions [66]

2.5 ECONOMICS OF BIOMASS ENERGY

Any system is not fruitful unless it is economical. Important papers related with economics of biomass are presented in this section.

Kiker and Eoff (1984) analysed and assessed the economic potential as per business environment in the United States for fuelling a 55 ha centre pivot irrigation arrangement with producer gas. To explore it simulation modelling is used under which a downdraft wood gasifier is economically reasonable to substitute a diesel fuel for a 55 kW engine is investigated. The gasifier system investment is reasonable under all conditions of market, even when diesel fuel is decreased from \$0.29 to \$0.25 per litre during the 10-year life. They also mentioned that the net present value of the producer gas system operational expenses will fall

between \$21800 and \$33700, while the net present value of the diesel system operational expenditure will fall between \$38100 and \$43 700 for the ten years

Rajwanshi and Joshi (1989) evaluated the economic experiences of powering a 3.75 kW diesel pump set by a topless hybrid gasifier. Financial investigation exposed that at 60% diesel replacement and timber cost of Rs 0.5/kg, the gasifier system is inexpensively comparable to stand-alone diesel water pumping systems (fig.2.1). Unavailability of easy funding for the procurement of the gasifiers at that time is the biggest blockage for their large scale use as an energy source for pumping water for irrigation is the other conclusion of their study.

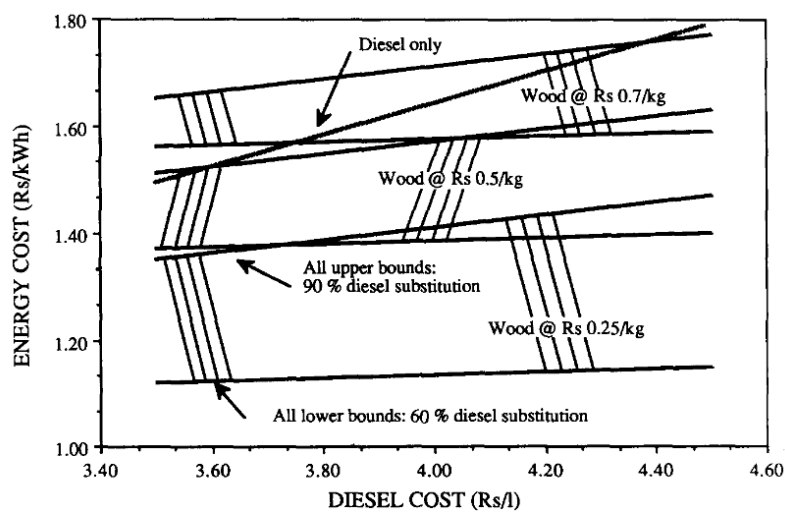


Fig.2.21: Effect of amount of diesel fuel and cost of wood on energy output [71]

Jorapur & Rajvanshi (1997) suggested the commercial scale (1080 MJ/h) development of a low density biomass gasification system for thermal application which can handle fuels like sugarcane leaves, bajra stalks, sweet sorghum stalks and bagasse, etc. They have been tested the system for 700 h under laboratory conditions of 287-1085 MJ/h output levels. The Higher heating value of the gas was 3.55-4.81 MJ/m observed. The system also produces char which is equivalent to 23wt% of the original fuel. From their results, it is also demonstrated that low density biomass gasifier running on sugarcane leaves or bagasse can be successfully retrofitted to existing oil fired furnace/boilers in metallurgical and other industries, if the cost of biomass is less than Rs.1350 per Tonne for capacity of 1080 MJ/h.

Tripathi et al (1998) discussed the availability of eight selected agricultural residues as raw material for biomass gasification in India with due consideration to their seasonal and geographical availability dimensions. Biomass residues of arhar stalk, maize stalk, maize cobs,

cotton stalk, mustard stalk, jute and mesta sticks, rice husk and groundnut shells have been assessed. It is reported that more than eight million tonnes of these residues were produced in the year with a primary energy potential of about 1200 Peta Joules. Cost estimates of biomass residues vary from Rs. 132/tonne to Rs. 628/tonne, depending on the agricultural residue cost and the transporting distance. These cost figures were much lower than the prevailing cost of coal in India. Hence, these agricultural residues may be profitably used as feedstock in biomass gasification and briquetting plants.

Table 2.3: Seasonal availability of agricultural residues [112]

Residue	Availability											
	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Arhar Stalk												
Maize Stalk												
Maize Cobs												
Cotton Stalks												
Mustard Stalks												
Jute and Mesta												
Rice Husk												
Groundnut Shells												

Table 2.4: Total cost of agriculture residues (Rs/Tonne) [112]

Residue	Animal cart	Tractor trolley		
	0-15 (km)	0-15 (km)	15-30 (km)	30-50 (km)
Arhar stalk	247	244	298	306
Maize stalk	302	298	325	360
Maize cobs	135	132	159	194
Cotton stalk	569	566	593	628
Mustard stalk	487	484	511	546
Jute and mesta sticks	302	299	326	361
Rice husk	237	234	261	296
Groundnut shells	507	504	531	566

Tripathi et al (1999) compared the unit cost associated with biomass based gasifier institutional cooking systems with that for liquefied petroleum gas and coal. They had modelled a mathematical formula for measuring the unit cost of all the three systems considering maintenance to labour cost. It had been calculated and presented that for biomass-based gasifier system it comes out to be Rs 0.38/MJ for a 29kW_{th} while for a 291 kW_{th} scheme it is Rs 0.24/MJ. On the other hand very small decline in the unit cost of thermal energy with a boost in the thermal ranking of LPG and coal-based systems is observed. The variation of thermal rating and cost associated are mentioned in Table 2.5.

From the overall analysis, it was concluded that biomass gasifier-based institutional cooking systems are always financially extra fruitful and fascinating option as compared to coal and LPG-based systems for capacities over 58 kW_{th}.

Table 2.5: Unit cost of thermal energy in institutional cooking systems [111]

Thermal Ratings(kW _{th})	Unit Cost of thermal energy(Rs/MJ)		
	Gasifier based system	LPG Burner	Coal Oven
17.5	0.44	0.34	1.26
29	0.37	0.34	1.25
58	0.32	0.34	1.25
116	0.28	0.34	1.24
291	0.23	0.34	1.24

Balat et al (2006) investigated the biomass sources and their trends of use in Turkey as an energy source. Annual biomass production potential of Turkey is 32 million tonnes and domestic energy consumption is 37% of total energy consumption. About 52% are coming from biomass-based fuels. The amount of usable biomass capacity of Turkey is approximately 17 million tonnes. In 1992, electricity production from biomass had a net impact of \$1.7 billion, and biomass electricity generation capacity will grow to 22 GW by 2010. At this capacity level, the economic benefits are calculated to be \$6.2 billion in personal as well as corporate income with 238,000 jobs. Also, the amount of usable biomass potential of Turkey is 6.2 GW and electrical production from usable biomass has a net impact of \$1.8 billion in the economy of Turkey.

Nouni et al (2007) presented the techno-economic evaluation of decentralised power supply for remote locations in India using biomass-based power projects. The levelized unit cost of

electricity delivered to the consumers has been supposed to be varying in the range of Rs. 13.14–24.49/kWh for dual fuel biomass-based gasifier power project. The levelized unit cost of electricity increases significantly if biomass-based gasifier power project is operated at part loads. Presently available 40 kW capacity 100 % producer gas systems in India are expected to be financially competitive with a diesel generator set of identical capacity beyond a break-even diesel price of Rs. 34.70 per Litre. It is predicted to be financially more attractive than an identical capacity dual fuel biomass-based gasifier power project for diesel prices of more than Rs. 44.29 per Litre. In certain specific conditions operating two smaller capacity systems has been found to be attractive as against a single larger capacity system.

2.6 REFLECTIONS

From the review of literature available in the field of biomass usage, many advantages are noticeable. The following are some of the advantages and challenges of using biomass as fuel with diesel in I.C. Engine in India [94, 108].

- Agricultural waste obtained domestically helps to reduce costly petroleum imports as India is an agricultural based country.
- Developing the biomass usage machinery would strengthen the domestic, and particularly the rural economy of India.
- It is non-toxic and biodegradable.
- It is a renewable fuel that is considered as waste till date.
- It contains no aromatics and sulphur.
- It has a reasonable cetane number and which reduces the knocking tendency.
- No major modification is required in the engine.
- Personal safety is improved as the flash point is higher than that of diesel.
- It is usable with the existing petroleum diesel infrastructure.

Challenges

The major challenges that face the use of Biomass as I.C. engine fuels are listed below [13, 57, 94].

- Biomass prices are dependent on various factors like availability, transportation, and drying, etc.
- Feedstock homogeneity, consistency and reliability are questionable.
- Stability in long term storage and handling are difficult
- Compatibility with I.C. engine material needs to be studied further.

- Engine manufacturer's acceptance is another major difficulty.
- Continuous availability of the particular type of biomass needs to be assured before embarking on the major use of it in I.C. engines.

Technical Difficulties

The major technical areas (with respect to the use of biomass as fuels in I.C. engines), which need further attention are listed below [13, 58, 94].

- Less expensive quality tests development
- A wide range of biomass feedstock's emission testing.
- Co-product utilisation like ash produced in a beneficial manner.
- Efforts to be focused on responding to fuel system performance, material compatibility and low fuel stability under long term storage.
- Continued engine performance, emissions and durability testing in a variety of engine types and sizes need to be developed to increase consumer and manufacturer confidence.
- Environmental benefits offered by biomass over diesel fuel needs to be popularised.
- Studies are needed to reduce cost and identify potential markets in order to balance cost and availability.

It was also reported that nearly 18,000 Indian villages cannot be electrified by the conventional grid, owing to their location in remote and difficult areas. Decentralized power generation and distribution using locally available resources is the only option for electrifying these villages. An image from NASA's Earth Observing System Data and Information System (EOSDIS) website on October 12, 2016 shows 'fire spots' dotting Punjab and northern Haryana (Fig3.1) and June 13, 2016 in Central Africa (Fig. 3.2). Each spot denotes thermal and fire anomalies detected by NASA's satellites. The maps give an idea about the geographic spread of crop burning. The fire patterns have been similar from last year. The problem of pollution caused by agricultural crop stubble burning has not received much attention by the policymakers and the various pollution authorities till recently.

Ever increasing fossil fuel consumption and associated demand, a large outflow of foreign exchange and concern for the environment have prompted focus towards analyzing a renewable, sustainable, cost effective, eco-friendly alternative fuel. With biomass satisfying all the above requirements and gasification being a fast developing bio-energy conversion

technique, it was decided to research on gasification of bio-residues for possible power generation.

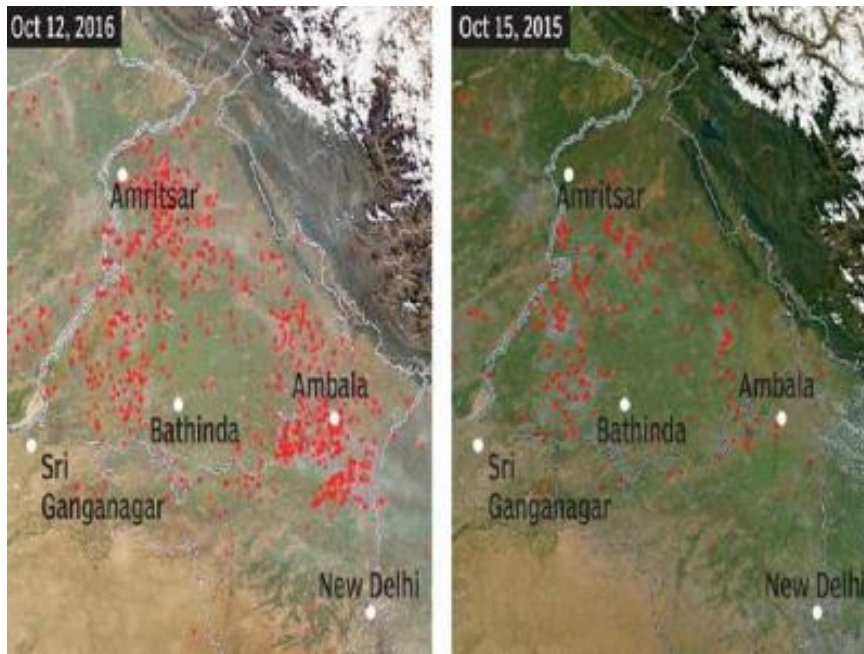


Fig. 2.22: Crop firing in North India [40]

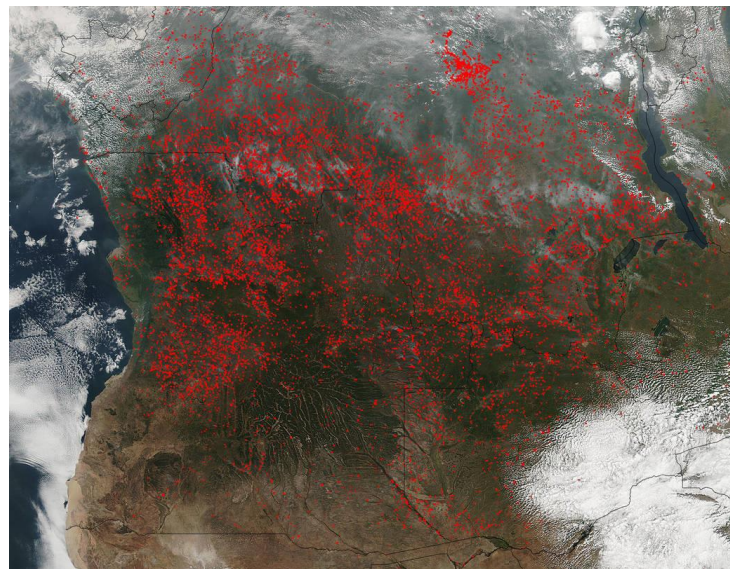


Fig. 2.23: Crop firing in Central Africa [43]

2.7 PROBLEM FORMULATION

From the above literature review it could be observed that, much of the attention is focused on biomass gasification from different woody biomass. Only few agricultural residues are studied and commercialised for power generation using gasification in India and other countries.

Availability of cotton stalk is significant and is widely distributed across the agricultural map of India. Research work on gasification aspects of Cotton stalk is observed to be minimal. Particle size distributions were studied in fluidised bed gasifier but limited work is present on the effect of particle size on the engine performance and emissions level in downdraft gasifiers. Techno-economic feasibility of biomass gasifier based power generating systems at lower installed capacities is also minimal. In addition to it particle size effects on producer gas composition and engine performance is also minimal.

Considering all the above parameters in mind following aims and objectives were planned in this work:

- i. To study the performance of 5 kW dual fuel engine using biomass fuel (cotton stalks) and diesel.**
- ii. To evaluate the emission levels of dual fuel engine using cotton stalks as feedstock in gasifier.**
- iii. To study the effect of composition of biomass on performance of dual fuel engine.**
- iv. To study the effect of particle size distribution and properties of fuel in the performance of dual fuel engine.**
- v. Economic analysis of the system**

The novelty of this work is to provide the particle size distribution effect on engine performance. In addition it will provide the techno-economic feasibility of biomass gasifier based power generating systems at lower installed capacities (house hold power generation or village level power generation). Small scale biomass gasification for power generation will be a cost effective and more environmentally friendly alternative to traditional energy sources. This will also act as a bridge for the gap between biomass resources and costs to design a framework for effective decision making in the biomass energy management in rural India.

CHAPTER 3

EXPERIMENTAL SETUP

In present study, cotton stalk is used as biomass fuel for gasification using a downdraft gasifier. Investigation of various performance characteristics of engine using producer gas generated from cotton stalks is done. Pre-processing of fuel required is also discussed and various problem insights are discussed.

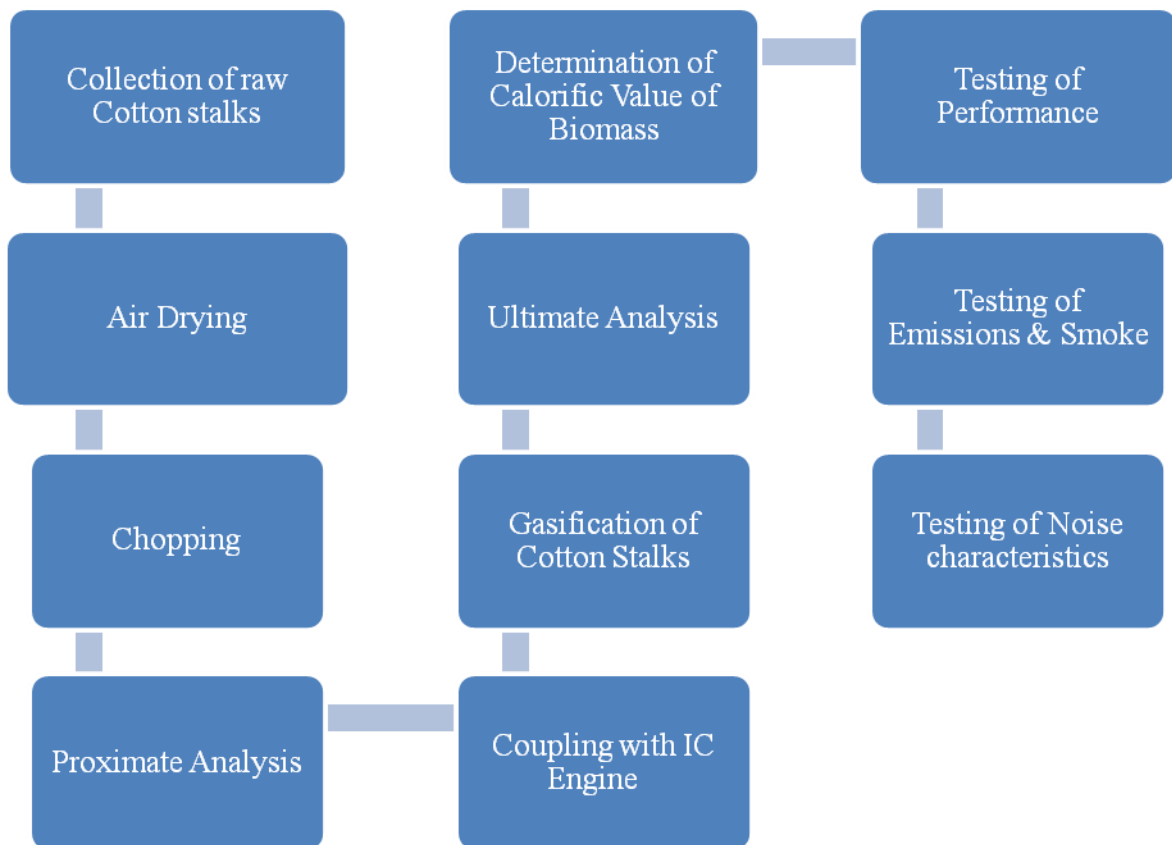


Fig.3.1: Flowchart of methodology used for experimentation

3.1 COLLECTION OF RAW MATERIAL

The 90.86 and 11.44 Mt of cotton and mustard stalks are available as dry residues in India out of their total stalk generation of 37.86 and 7.17 Mt, respectively. The major states Gujarat, Maharashtra, Haryana, Punjab, Rajasthan and Karnataka have the major stake in cotton stalk generation in India. 100 kg of raw cotton stalk was collected from a farmer friend of Village Chughe Khurd Distt. Bathinda. Raw cotton stalk was air dried for one week.



Fig.3.2: Raw cotton stalks hulls.



Fig.3.3: Cotton stalk shredder

3.2 CHOPPING

Air dried raw cotton stalks are chopped in required size range i.e. below 20mm using cotton stalk shredder at Satwant Agro Industry Bhawanigarh. The shredded cotton stalk biomass was used as feed material in the downdraft biomass gasifier. The complete cotton stalk biomass was difficult to use directly in the gasifier so the shredded cotton stalk was used as feeding material. The complete cotton stalk was converted into shredded material with the help of cotton stalk shredder. The capacity of cotton stalk shredder machine is 3.5 kg/min. The processed cotton stalks have moisture content less than 10% and maximum size of processed cotton stalks is 20mm.

3.3 PROXIMATE ANALYSIS

For determination of moisture content, fixed carbon, volatile matter and ash content of processed cotton stalks, proximate analysis is done on air dried basis. The proximate analysis of sample was carried out in accordance with ASTM D3172-73 (1984) standard. The volatile matter contents in the test sample were determined according to ASTM D3175-89. Determination of ash content in the test sample was carried out according to ASTM D3174-89 method in the electric furnace. The fixed carbon content of the test sample was calculated by difference. 2gm cotton stalk is taken for testing of proximate analysis. Small silica crucible is used for the testing. Silica crucible taken is cleaned and dehydrated using an electric oven set at temperature of 110°C. Silica crucible is then cooled to normal temperature by keeping it in open for 15 minutes and after this it is weighed accurately using digital weighing machine. The sample taken in crucible is placed in an electric oven for removing moisture. Samples are heated for 1 hour at 110°C and they are stirred after short intervals so that effective evaporation of moisture can take place by exposure of lower biomass. After removing the sample from the oven, it is placed in desiccators. The sample is weighed again and the decrease in mass gives the moisture content of sample. To calculate the VM (Volatile Matter), the sample is heated at 240°C in a muffle furnace for half an hour. After cooling the sample in desiccators, it is weighed and this loss in mass gives the VM in the sample. Further the sample is heated in the muffle furnace at 600°C and it is burnt to ashes. Finally the sample is weighed again and this loss in mass gives the ash content in the sample.

The percentage volatile matter (V.M) was determined as follows:

$$\% \text{ VM} = \frac{m_s - m_{fd}}{m_s} \times 100 \% \quad (3.1)$$

Where, m_s = mass of air dried sample,

m_{fd} = mass of sample after 10 minutes in furnace at 900°C.

The percentage ash content (A) was determined as follows:

$$\% \text{ ASH} = \frac{m_{ar}}{m_s} \times 100 \% \quad (3.2)$$

Where, m_{ar} = mass of ash residue (g),

m_s = mass of air dried sample (g).

The fixed carbon in the sample is given by the following relation:

$$\text{FC} = \text{Total weight} - (\text{Moisture} + \text{VM} + \text{Ash}) \quad (3.3)$$

Table 3.1: Proximate analysis of biomass samples (air dried basis).

Biomass / characteristics	Cotton stalks %w/w;	Sugar cane Bagasse %w/w;	Wood chips %w/w;
Fixed Carbon	22.4	20.1	21.7
Volatile Matter	70.89	73.8	70.4
Ash Content	6.68	4.27	3.2
Moisture	<10.00	<10.00	<10.00

3.4 CALORIFIC VALUE

The higher heating value of these samples was determined according to ASTM D2015-(1985) method in an oxygen bomb calorimeter. Oxygen bomb calorimeter was used for measuring the CV of cotton stalk; 1 gm. of sample was taken in a nichrome crucible. To facilitate the ignition a 15 cm long cotton thread was placed over the sample in the crucible. A nichrome fuse wire was connected with both the electrodes of the calorimeter. Oxygen gas was filled in the bomb at a pressure of around 25 to 30 atm. The water taken in the bucket was constantly mixed to homogeneous the temperature. The sample was ignited by switching on the current through the fuse wire and the rise in temperature of the water was accordingly recorded. The following formula was used to determine the energy value of the sample.

$$CV = (2382.32 * T/x) \times (m_1 + m_2) \quad (3.4)$$

T=change in temperature of water

x=weight of sample (cotton stalk)

m_1 and m_2 are mass of water in copper calorimeter and water equivalent of bomb calorimeter respectively.

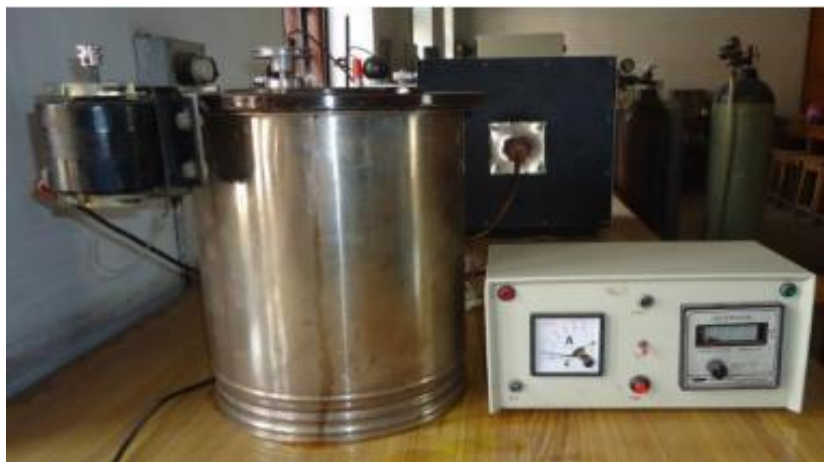


Fig.3.4: Oxygen bomb calorimeter

Table 3.2: CV of biomass samples

Biomass / characteristics	Cotton stalks	Sugar cane Bagasse	Wood chips
Higher Heating Value, MJ/kg	17.4	18.11	17.4

3.5 ULTIMATE ANALYSIS

This analysis was done in the National Fertilizers Limited Bathinda Chemical Laboratory by using CHONS Analyzer (ASTM Standard D5373 –02). The report of ultimate analysis is as follows.

Table 3.3: Results of ultimate analysis using CHONS analyzer

Biomass / characteristics	Cotton stalks	Sugarcane Bagasse	Wood chips
Carbon	43.64	44.8	48.6
Hydrogen	5.81	6.2	5.56
Oxygen	43.87	44.4	41.46
Nitrogen	0	0.2	0.6
Sulphur	0	0.01	0.03

3.6 GASIFIER SYSTEM

The current study was completed using downdraft gasifier in the university campus for finding out the performance and emission characteristics of dual fuel engine using producer gas of cotton stalks. The specifications of the gasifier were provided in Table 3.4 and are according to the catalogue of setup authenticated by the company itself.



Fig 3.5: Gasification system used for study

Table 3.4: Specifications of gasifier system.

Gasifier Make	Ankur Scientific Energy Technologies Pvt.Ltd.
Gasifier model	WBG-10
Type	Downdraft with throat
Material of Construction	Mild Steel, Stainless (SS 310) and moulded refractory cement
Number of Air Nozzles	2
Flow rate (Nm ³ /hr)	25
Hopper capacity (kg)	60
Combustion Zone Temperature (°C)	1100
Avg. Gas Calorific Value (kJ/Nm ³)	4393.2 to 5439.2
Start Up	Through engine suction / blower
Gas composition	CO = 19 ₊₃ % , H ₂ = 18 ₊₂ % , CO ₂ = 10 ₊₃ % , CH ₄ = upto 3% , N ₂ = 50%
Thermal Output(kW)	30.21
Dry Filter	
Type	Packed bed
Material of construction	Mild Steel
Fitter Medium	Sawdust
Biomass Fuel	
Type	Wood/Woody Waste/Agricultural waste

Maximum Dimension of Solid Fuel	Not exceeding 25 mm
Size Distribution	Random
Maximum Moisture	5 to 20% (Wet basis)
Charging	Batch mode, by topping up once every six hours.
Hourly Consumption	8 to 10 Kg.

The gas is first passed through scrubber in which a water spray helps in cooling the gas and it also removes water soluble gases like HCl, H₂S, SO₂ and NH₃. Excessive soot particles and tars present in gas are also removed by scrubber by condensing them. This gas was further passed through a drum like structure known as secondary filter, which contains sawdust and wood chips.



Fig 3.6: Air opening with cap



Fig 3.7: Filters for ultra-cleaning of the gas

Gas passes through the voids present in wood chips and sawdust but other particulate matter gets trapped in it. This filter also absorbs moisture along with trapping of the soot particles. Gas temperature at the outlet of secondary filter is around 50° C. To ensure complete cleaning of the gas, the gas is further passed through a safety filter which is relatively smaller in size. It contains a filter paper which is capable of absorbing very minute soot particles and provides very clean gas. This gas at outlet of safety filter is ~99% pure and has a temperature of 30° C-45° C. This gas is safe to be used in IC engines without causing any problems.

3.6.1 Precautions:

- Clean the ash from the reactor after short period.
- Strictly maintain the moisture content and size of the biomass samples.
- When the gasifier system is in operating condition, no parts of the gasifier and other sub systems other than the feed door of the hopper are to be opened. They should be opened only when the gasifier system is not in operation and cooled down.
- Care should be taken so that the foreign matter e.g. sand, nails, stones etc. are not poured into the hopper along with the prepared biomass.

3.7 PROBLEMS FACED IN GASIFICATION SYSTEM

- Bridging and jamming associated with handling of feed and / or ash either inside or outside gasifier.
- There is no gas reservoir to store and control the gas when gasifier is running in a single mode (diesel) mode. Also in a dual mode, a part of the gas that is producing in the hopper is allowed to go inside the cylinder. There is no space to store remainder part.
- Lack of proven gas clean up systems which results in tar build up on the valves and fast wearing of engine cylinder and pistons. This in turn results in frequent overhaul of the system.
- Lack of data to carry out proper modifications in air-fuel mixing systems as well as the engine.
- Producer gas is a low heating value gas, which is poisonous and explosive. Hence, proper carbon monoxide metering arrangements as well as safety devices needs to be provided.

3.8 PARTICLE SIZE DISTRIBUTION

Particle size distribution of cotton stalk collected from agricultural field is shown in Table 3.5 as per sieve analysis following the **ASTM C136** standards.

Table 3.5: PSD analysis of cotton stalks

Range of Sieve Size (mm)	Mesh Size, ϕ (mm)	Mass retained (gms)	Mass retained (%)	Cumulative mass	
				Oversize (%)	Undersize (%)
-3 + 2	2	3	3.03	3.03	96.97
- 4 + 3	3	14.3	14.44	17.47	82.53
- 5 + 4	4	72	72.73	90.20	9.80
- 6 + 5	5	2	2.02	92.22	7.78
- 8 + 6	6	3.2	3.23	95.45	4.55
- 10 + 8	8	3	3.03	98.48	1.52
+ 10	10	1.5	1.52	100.00	0.00

The goal of this work is to obtain a distribution function $F(\phi)$ (mass fraction) of the sample of waste cotton stalks using Rosin-Rammler (RR) and Gates-Gaudin-Schuhmann(GGS) mathematical models applied to data obtained by sieve analysis of cotton stalks. The RR model distribution function was used to describe the particle size distribution of powders of various sizes and types. The function is particularly suited to represent powders made by grinding, milling, and crushing operations. The general expression of the RR model is:

$$F(\phi) = 1 - \exp\left[-\left(\frac{\phi}{l}\right)^m\right] \quad (3.5)$$

where,

$F(\phi)$ = distribution function

ϕ = particle size (mm)

l = mean particle size (mm) or size modulus

m = measure of the spread of particle sizes or distribution modulus

The utilisation of the function to a particular distribution calculation of its parameters is often performed by linear regression data, expressed as $\ln\{-\ln [1-F(\phi)]\}$, versus $\ln\phi$, indicating the applicability of RR model for particle size distribution curve. The correlation

coefficient is used as a parameter indicating the relevance of the measured data set. Another popular model for determining particle size distribution is the GGS model; due to its simplicity and clarity in application it has been used in industry since 1940 and is defined as

$$F(\phi) = \left[\frac{\phi}{\phi_{max}} \right]^m \quad (3.6)$$

where,

$F(\phi)$ = the fraction of the sample finer than size ϕ

ϕ = particle diameter (mm)

ϕ_{max} = particle diameter (mm)

m = distribution modulus

A plot of the logarithm of the distribution function versus the logarithm of the particle diameter of the tested material is shown as a straight line for the particle size distribution fits the RR model.

3.9 COMPOSITION OF PRODUCER GAS

This analysis was done in the Central Pollution Control Board, New Delhi by using Gas Chromatography (NUCON5765) by offline method. The septum port gas sampling tube (Gas Sampling Bulb) as shown in Fig. 3.8 is used for collecting the gas sample from gas pipeline for gas chromatography. It has two stopcocks at either end to allow the flow of gas through the tube. The gas will be extracted by piercing the septum port on the side arm with a syringe for analysis in gas chromatography unit.

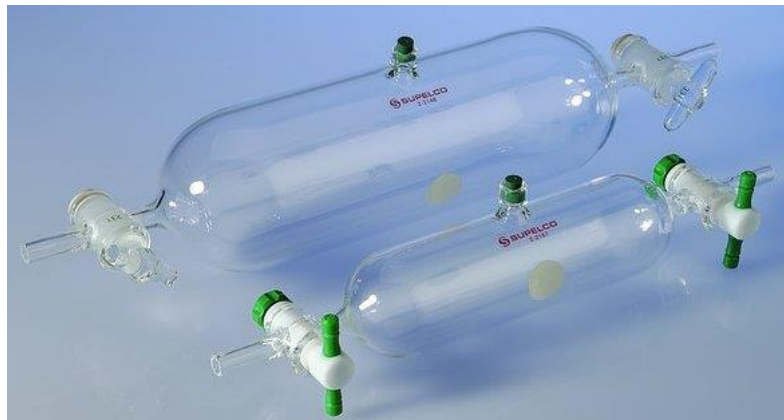


Fig 3.8: Gas Sampling Bulb

Initially the one end of the glass bulb with the collecting port is being connected. Carefully open the inlet valve on the bulb and allow 5 or 10 seconds for the cylinder to become pressurized. Close the bulb inlet valve and then open the outlet valve to vent the gas. Leave the outlet valve open just until we can no longer hear gas escaping, and then close it. When the bulb has been adequately flushed, check to see that the bulb outlet valve is firmly closed and then open the inlet valve one more time. Allow 20 or 30 seconds for the bulb to become pressurized and then close the inlet valve. Now the gas sample is ready for transferring to the gas chromatography unit where gas composition analysis will be done.

Final report of producer gas is as follows.

Table 3.6: Composition of gas produced from gasifier

Gas	For 10 mm particle (%)	For 15 mm particle (%)
Methane	1.8	1.52
Carbon Monoxide	19.3	22.83
Carbon Dioxide	11.92	9.67
Hydrogen	17.46	15.3

3.10 DUAL FUEL ENGINE SETUP

The clean producer gas obtained after the cleaning process is sucked by the engine and is introduced into the inlet manifold of the dual fuel engine. Mixing of producer gas with inlet air takes place in inlet manifold of engine. The flow rate of producer gas being sucked by engine is measured by using an orifice type flow meter. It gives the readings in the form of pressure drop of water in a U-tube manometer. Fig 3.8 shows the schematic representation of the method used for mixing and introducing producer gas into the DFCI engine. Engine used for experimentation is a dual fuel compression ignition single cylinder engine. It is electric start and water cooled. A governor is employed to control speed fluctuations and due to this engine runs at almost constant speed of approximately 1500 RPM. The set-up enables the study of the engine for P- θ diagram, indicated power, brake power, thermal efficiency, volumetric efficiency, fuel consumption, air-fuel ratio, heat balance etc.



Fig 3.9: Flow meter used to measure flow rate of producer gas.

The various emission and performance parameters of DFCI engine were studied by keeping the compression ratio of the engine 18:1. The gas flow rate was controlled by adjusting the flow rate control valve and flow rate was fixed to $5.07\text{Nm}^3/\text{hr}$. In order to ensure the repeatability and the correctness of experiments, keeping all parameter same, three trials of all the tests were conducted. The engine was tested on Dual fuel mode using diesel oil as primary fuel and producer gas secondary fuel. Before starting the engine, water valve was opened to supply cooling water to the water jacket.

250 LPH to 75 LPH water was supplied to the engine for cooling. The engine was fixed for five loads from 1.91kg to 9.93kg. Air flow and gas flow rates were recorded using two orifices of 20 mm and 15.31 mm diameters, respectively. All the graphs were represented using these average values of the corresponding parameter.

The various other specifications of engine used for study are shown in table below.

Table 3.7: Specifications of the DFCI engine setup.

Product	VCR engine test set up diesel (computerised)
Engine	Make Kirlosker ,Single cylinder,4 stroke diesel, water cooled , Power 5.0 kW at 1500 rpm, stroke 110 mm, bore 37.5 mm,553cc,CR 17.7,modified to VCR engine CR range 12 to 18,electric start
Dynamometer	Type eddy current , water cooled with loading unit
Air box	MS fabricated with orifice meter and manometer
Fuel tank	Capacity 15 litres with glass fuel metering column
Piezosensor	Range 5000 PSI, with low noise cable.
Crank angle sensor	Resolution 1 deg, speed 5500 rpm with TDC pulse
Data acquisition device	NI USB-6210,16 bit,250 Ks/s
Temperature sensor	Type RTD,PT100 and thermocouple, type K
Load indicator	Digital, range 0-50 kg , supply 230 VAC
Piezo powering unit	Make CUADRA , model AX-409
Digital mill voltmeter	Range 0-200mV.panel mounted
Software	" Engine soft LV" engine performance analysis software
Rotameter	Engine cooling 40-400 LPH; calorimeter 25-250LPH
Pump	Type monoblock
Fuel	Diesel alone and blends of diesel and producer gas



Fig 3.10: Dual fuel engine setup coupled with a dynamometer



Fig. 3.11: Complete setup of engine test rig

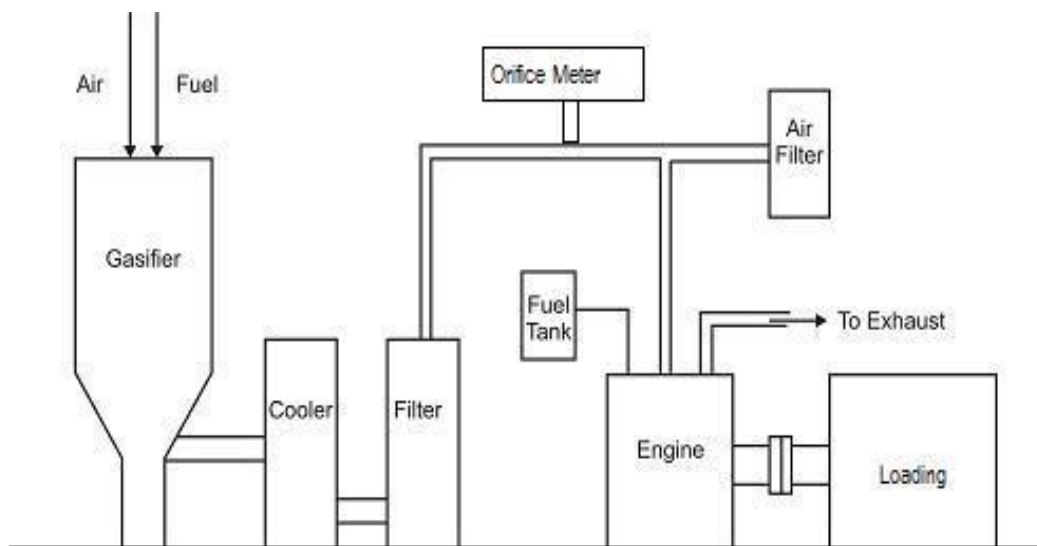


Fig. 3.12: Complete schematic arrangement of experimental set up

3.10.1 Engine

The test engine used in the present work is a single cylinder, naturally aspirated, direct injection compression ignition engine of Kirloskar make. This diesel engine has a bore of 80mm and stroke of 110mm. The specification of the engine is shown appendix -A. The engine has a rated output of 5HP at a speed of 1500 rpm. The engine was coupled to an eddy current type dynamometer to apply the load on the engine with an electrical panel. The engine is mounted on a stationary frame with a suitable cooling system. The lubricating system is inbuilt in the engine.

3.10.2 Dynamometer

The engine is connected to a swinging – field electrical generator meter with Ward – Leonard control that allowed the engine to be started and motored likewise. The load is controlled by dynamic changing the field sector current. The reading of load (voltage and current) is noted from the data acquisition panel board fixed to engine test setup by the manufacturer and the power absorbed is calculated. The experimental study is conducted at various loads and hence an accurate and reliable load measuring system is a must. The load measuring system of this experimental test rig consists of a dynamometer of eddy current type, a load cell of strain gauge type and a loading unit. The load is applied by supplying current to the dynamometer using a loading unit. The load applied to the engine is measured by a load cell. A dynamometer is a device which is used for measuring force, torque or power produced by an engine. It can also be used to apply load or torque on the engine. The dynamometer used in this study is an eddy current type with a water cooling system. The eddy current dynamometers provide an advantage of quicker rate of load change for rapid load setting. The eddy current dynamometer unit basically comprises of a rotor, shaft, bearings, casing and bed plate. The rotor is mounted on the shaft which runs in the bearings. The bearings rotate within the casing supported in ball bearing, which form a part of the bed plate of the machine. Inside the casing, there are two field coils connected in series. When a direct current is supplied to these coils using a loading unit, a magnetic field is created in the casing across the air gap on either side of the rotor. When the rotor turns in this magnetic field, eddy current gets induced creating a braking effect between the rotor and the casing. The rotational torque exerted on the casing is measured by a strain gauge load cell incorporated in the restraining linkage between the casing and the dynamometer. A load cell is a transducer that is used to convert a mechanical signal (force) into an analogous electrical signal. The loading unit consists of a dimmer stat to control the magnitude of the direct current flowing into the dynamometer.

3.10.3 Speed measure

The speed of the engine is measured by using an electromagnetic pickup in conjunction with a digital indicator fixed to data acquisition panel board. A magnetic pickup is fitted near the fly wheel of the engine with pins mounted on the periphery. The signals generated are fed to the show unit that is graduated to point the speed directly in range of revolutions per minute (rpm).

3.10.4 Measurement of Fuel Consumption

Fuel is provided to the engine from the fuel tank through Fuel sensor and glass tube mounted to the fuel tank which is fixed to data acquisition panel board. The rate of fuel flow is found by measuring the time required for the consumption of a known amount of fuel i.e. 10 cc from the measuring instrument.

3.10.5 Exhaust Gas Temperature measurement

A Nickel-Nickel chromium thermocouple fixed to the exhaust manifold of the engine exhaust valve is employed for measure of exhaust gas temperature. The reading of Exhaust gas temperature is noted from the data acquisition panel board fixed to engine test setup by the manufacturer.

3.11 EXPERIMENTATION METHODOLOGY

For purpose of comparison, performance and emission parameters and noise characteristics of engine are tested in two modes:

- Normal diesel only operation.
- Dual fuel mode using diesel and producer gas.

The performance of the engine is evaluated in terms of brake thermal efficiency, brake specific energy consumption, exhaust gas temperature, and emission of the engine is analyzed in relation with smoke, HC, CO, and NO_x. Also, noise level at different load is also evaluated. It also found out economic viability.

3.11.1 Experimentation Procedure

1. Check for all electrical connections and proper earthing for the equipments.
2. Ensure water in the main water supply tank.
3. Ensure selected fuel about 2 litre in quantity in the fuel supply tank and fuel knob on regular position.
4. Start water pump. Set cooling water flow for engine at 300 LPH and calorimeter flow at 80 LPH. Maintain this flow rate throughout the experiment. Ensure that adequate water flow rate for dynamometer cooling and piezo sensor cooling.
5. Start electric-supply to the computer through the stabilizer and open the engine software.
6. Set the load to minimum position using the rotary knob.
7. Start electric power supply to the smoke meter and flue gas analyser.

8. Start the engine ignition switch so that the engine will be cranked by battery. Let the engine run on the minimum load.
9. Change fuel properties (calorific value and specific gravity) in the software in the 'configure' option as per the fuel selected for test.
10. Choose run option in the software. Run the engine for fifteen minutes so that engine gets stabilized. Ensure that smoke meter have reached their default display and then turn the fuel supply switch to metering position. Choose log option of the software. After 1 minute the display changes to input mode then enter the values of water flows in cooling jacket and calorimeter and then the file name (applicable only for the first reading) in the software. The first reading for the engine gets logged for the no load condition. Turn the fuel knob back to regular position.
11. Open valve of the smoke meter and flue gas analyser connection. By closing the back-pressure valve and take the reading for smoke and flue gases when the value has stabilized.
12. Change the load to 1kg gradually by rotating the loading knob and observing in the monitor for load value. Allow the engine to run for 10 minutes for stabilization at new load. After stabilization again turn the fuel knob to metering position and choose the log option from software. After one minute after the fuel logging is over, feed the cooling water and calorimeter flow rates and turn back the fuel knob to regular position. Take the reading of smoke meter and flue gas analyser as mentioned above.
13. Repeat the procedure for loads of 2, 3, 4, 5, 6 ...12 kg.
14. Reduce the load to minimum position (no load condition) gradually ensuring that the RPM's are not shooting beyond 1550 RPM and allow the engine to stabilize.
15. Save the files with appropriate names.
16. Put off the engine and computer.
17. Allow the water pumps to be on for 15 minutes so that engine gets cooled down and then put off the pumps.

3.11.2 Measurement of Parameter regarding engine performance and exhaust emission

The computerised CI engine set up along with a high-speed digital data acquisition system was supplied by Apex Innovations Pvt. Ltd., Sangli, India. An eddy current dynamometer, a piezoelectric transducer and digital PT-100 type temperature sensor was calibrated and used in the setup by Apex Innovations. Following parameters were measured from the experimental DFCI engine setup.

1. Brake power

2. BMEP
3. Brake thermal efficiency
4. Specific fuel consumption
5. A/F ratio
6. Exhaust gas temperature
7. Smoke, NO_x, UBHC and CO

3.12 MEASUREMENTS OF PERFORMANCE PARAMETERS

Internal combustion engine generally operates with in a useful range of speed. Some engines are made to run at fixed speed (optimum speed) by means of speed governor which is its rated speed. At each speed within the useful range the power output varies and it has maximum usable value. The ratio of power developed to the maximum usable power at the same speed is called the load. The specific fuel consumption varies with load and speed. The performance of the engine depends on inter-relationship between power developed, speed and specific fuel consumption at each operating condition within the useful range of speed and load.

The term performance usually means how well an engine is doing its job in relation to the input energy or how efficiently it provides useful energy in relation to some other comparable engines. The performance of an engine judged from the point of view of the two main factors, which are engine power and engine efficiency. Further to see how efficiently the conversion of fuel energy to engine power is carried out, is studied from the efficiency and specific fuel consumption curves.

Brake power is one of the most important parameter in the engine experiment. The SAJ make AG 20 eddy current dynamometer was used for present investigation. The fuel consumption of an engine is measured by determining the time required for consumption of given volume of fuel using a glass burette. The mass of fuel was calculated by multiplying volumetric fuel consumption to its density. An air box with orifice meter and manometer was used for accurate volumetric measurement of air consumption and finally mass flow rate was determined. Digital PT-100 type temperature sensor was used for temperature measurement.

3.12.1 Brake mean effective pressure

The BMEP is an important concept for improving different fuels. It is the average pressure the engine can exert on the piston through one complete operating cycle. It is the average pressure of the gas inside the engine cylinder based on neat power. BMEP is important because it is independent of the RPM and the size of the engine. Thus, all of the following plots in the next chapter will be plotted against BMEP. The BMEP (bar) is expressed as follows

$$BMEP = \left(\frac{4\pi T}{V_H} \right) \times 10^{-2} \quad (3.7)$$

where T (N m) is the brake torque, and V_H (L) denotes the engine total displacement volume.

3.12.2 Brake specific fuel consumption

It defined as the fuel flow rate per unit power output. It is a measure the efficiency of the engine in using the fuel supplied to produce work. It is desirable to obtain a lower value of BSFC meaning that the engine used less fuel to produce the same amount of work. This is one of the most important parameters to compare when testing various fuels. The BSFC is expressed as follows (g/kWh)

$$BSFC = \frac{M_A / AFR}{P} \quad (3.8)$$

where M_A is the mass flow rate of intake air (g/h) and P(kW) is the brake power.

$$P = T \left(\frac{2\pi N}{60} \right) \times 10^{-3} \quad (3.9)$$

where N is engine speed N (r/min).

3.12.3 Brake thermal efficiency

It is the ratio of the thermal power available in the fuel to the power the engine delivers to the crankshaft. This greatly depends on the manner in which the energy is converted since the efficiency is normalized with fuel heating value. The brake thermal efficiency, BTE (%), is expressed as follows

$$BTE = \left(\frac{3600}{BSFC \times LHV} \right) \times 100 \quad (3.10)$$

where LHV is the lower heating value of fuel (MJ/kg).

3.12.4 Exhaust gas temperature

Exhaust gases of an I.C. engine contain significant enthalpy and may contain unburned combustion products (Hydrocarbon). When the air fuel ratio is high, the amount of incomplete combustion products is likely to be low; there is an insufficient amount of oxygen to complete combustion. The exhaust temperature is related to the determination of system efficiency.

3.13 MEASUREMENTS OF EMISSIONS AND NOISE CHARACTERISTICS

3.13.1 Smoke Meter

In the present work AVL 437-smoke meter manufactured and marketed by M/S AVL India Pvt.Ltd, Gurgaon, and tested and approved by ARAI Pune is used for measuring the smoke density. It measures the opacity of the polluted air, in particular diesel exhaust gases in a measurement chamber of defined measurement length. The AVL smoke meter used for smoke opacity as shown in Fig 3.12.



Fig.3.13: AVL smoke meter used for smoke opacity

3.13.2 Flue Gas Analyzer

Flue gas analysis from engine was done by the Sophisticated Analytical Instruments Laboratories Society (SAI Labs, Patiala) using Flue gas Analyser (KM9106) for carbon monoxide and nitrous oxide and Flue gas analyser (Horiba) for unburnt hydrocarbons.

3.13.3 Noise Characteristics

In the present work SC-310 –sound level meter manufactured and marketed by M/S CESVA, Spain, and tested and approved by ARAI Pune is used for measuring the sound or noise level. It measures the noise produced during the running of engine. The CESVA sound level meter used for noise characteristics is shown in Fig 3.13.



Fig. 3.14: Sound level meter used for noise characteristics

CHAPTER 4

RESULTS AND DISCUSSIONS

The design and operation of biomass combustion systems depend upon several biomass characteristics, called, heating value, ash, moisture content and elemental composition. The heating value of a fuel can be reported in terms of a lower (LHV) or higher (HHV) value. Experimentally heating value of a biomass fuel can be determined by employing bomb calorimeter which determines the enthalpy change between reactants and products. The use of bomb calorimeter, though relatively simple and accurate, may not always be easily accessible to researchers. To overcome this issue, researchers with control of an elemental analyzer usually conduct proximate and ultimate analysis and subsequently use the measured data to determine the heating value via accepted empirical correlations.

The proximate analysis gives fixed carbon (FC), volatile matter (VM) and ash content (ASH) as solid, gaseous, and non-combustible components, respectively in any solid fuels [58]. The proximate analysis determines the overall biomass components in terms of fixed carbon, volatile matter, ash and moisture content of the fuels. The proximate analysis is also a simple and cheap method of investigating properties of biomass. Hence, recognition of proximate values based correlations for calculating higher heating values of fuels is increasing.

Over the past three decades, more significance on renewable fuels has led many scholars to find empirical correlations based on data from proximate as well as ultimate analysis of fuels, with specific focus on various types of woods. Tillman suggested that HHV of biomass material is a very strong function of its carbon content and is a popular correlation used to estimate the HHV of wood and wood bark. There are also researchers that propose HHV correlations based on experimental characterization of combined organic-based compounds (i.e. biomass and non-biomass materials).

The correlations based on the proximate analysis had low accuracy because the proximate analysis would provide only an empirical composition of the biomass while the correlations based on the chemical analysis were not reliable because of the variation of the component properties. The development of new correlation itself is not sufficient but error analysis is equally important to make sure the accuracy of the estimated results. [Table 4.1](#) summarizes proximate and ultimate analysis based existing correlations for various solid fuels from published literatures. In this study, a new empirical correlation based on proximate as well as ultimate analyses of biomass (lignocellulosic compounds) used for prediction of HHV presented. The correlation afford an easier, more cost-effective and faster alternative to predict HHV and are particularly useful for

researchers without access to the comparatively more expensive and sophisticated equipments for experimental HHV determination.

Table 4.1: Various Correlations from Literature

Proximate Analysis Equations		
I	$HHV = 0.3536FC + 0.1559VM - 0.0078ASH$	Parikh et al(2005)
II	$HHV = 0.2601FC + 0.2218VM - 3.0368$	Changdong Sheng(2005)
III	$HHV = 0.3543FC + 0.1708VM$	Cordero et al(2001)
IV	$HHV = 0.312FC + 0.1534VM$	Demirbas(1997,2001)
V	$HHV = 0.3133(FC + VM) - 10.81408$	Jimenez and Gonzalez(1991)
Ultimate Analysis Equations		
I	$HHV = 0.301C + 0.525H + 0.064O - 0.763$	Jenkins(1985)
II	$HHV = 0.341C + 1.322H - 0.12O - 0.12N + 0.0686S + 0.0153ASH$	IGT(1978)
III	$HHV = 0.3516C + 1.16225H - 0.1109O + 0.0628N + 0.10465S$	Boie (1987)
IV	$HHV = 0.3491C + 1.1783H + 0.1005S - 0.1034O - 0.0151N - 0.0211ASH$	Channiwala and Parikh(2002)
V	$HHV = 0.3259C + 3.4597$	Changdong Sheng(2005)

Also, the diluents effect of mineral matter/ash is considered in the development of the correlation. The data containing a large number of biomass materials like pits, shells, seeds, energy crops, cobs, fuel wood, bark, hull-husk, straws, stalks, fibrous materials etc., from the published literature have been used to cover different values of fixed carbon, volatile matter , ash, carbon, hydrogen, sulphur, oxygen and nitrogen contents. An exhaustive computer algorithm has been developed based on generalized method of least squares to formulate the new correlations expression. It is worth to note that the algorithm is capable to incorporate any number of variables and data points. Using this algorithm and 100 data points the new correlation is derived. The new derived correlations are given as

$$HHV = 0.1337FC + 0.2029VM - 0.058ASH \quad (4.1)$$

$$HHV = 0.404C - 0.5267H + 0.3318O - 7.316N + 18.987S - 10.1247 \quad (4.2)$$

where, HHV refers to higher heating value (MJ/kg, dry basis) , FC, VM and ASH are fixed carbon, volatile matter and ash contents respectively, both in weight percent on a dry basis.

Also, C, H, O, N, and S are the carbon, hydrogen, oxygen, nitrogen and sulphur contents as elemental composition in biomass. To compare the present equation with existing ones, five equations have been selected from the literature for proximate and five equations for ultimate analysis (Table 4.1). Table 4.3 and 4.4 show the heating values calculated from these equations for sample ten biomass samples used for the present work. To facilitate the selection of correlation, three statistical parameters are employed as evaluating parameters which are defined as follows:

Absolute Average Error (AAE) is given as

$$AAE = \left(\frac{1}{n}\right) \sum_{i=1}^n \left| \frac{HHV_C - HHV_M}{HHV_M} \right| \times 100 \% \quad (4.3)$$

Average Bias Error (ABE) is given as

$$ABE = \left(\frac{1}{n}\right) \sum_{i=1}^n \left(\frac{HHV_C - HHV_M}{HHV_M} \right) \times 100 \% \quad (4.4)$$

Coefficient of correlation (R^2) is given as

$$R^2 = \frac{\sum HHV_C HHV_M - \sum HHV_C \sum HHV_M / N}{\sqrt{[\sum HHV_C^2 - (\sum HHV_C)^2 / N]} \sqrt{[\sum HHV_M^2 - (\sum HHV_M)^2 / N]}} \quad (4.5)$$

Where HHV_C = calculated HHV (MJ/kg)
 HHV_M = measured HHV (MJ/kg)
 N = number of samples

Table 4.2: Sampled 10 biomass proximate and ultimate analysis data for validation

Biomass	Fixed Carbon %	Volatile Matter %	Ash %	C %	H %	O %	N %	S %	Higher Heating Value, MJ/kg
Cotton stalks	22.42	70.89	6.7	43.6	5.8	43.9	0	0	17.4
Sugar cane Bagasse	21.1	74.7	4.2	44.8	6.2	44.5	0.2	0	18.11
Rice husk	17.4	64.8	18	38.6	4.8	38.4	0.4	0	14.4
Rice straw	18.7	69.8	12	41.8	5.6	40.4	0.7	0	12.1
Wood chips	21.8	74.4	3.8	48.6	5.6	41.5	0.5	0.1	17.4
Neem wood	12.19	85.86	1.9	48.3	6.3	43.5	0.1	0	20.257
Mango wood	11.36	85.64	3	46.2	6.1	44.4	0.3	0	18.17
Eucalyptus wood	21.3	75.35	3.4	46	5.8	44.5	0.3	0	17.84
Sagoon wood	14.9	77.4	7.7	39.8	5.6	46.8	0.2	0	17.41
Mustard stalks	21.9	60.9	17	45.3	5.1	31.4	0.7	0.4	17.49

Table 4.3: Comparison with other Equations from the Literature and new correlation

Biomass	HHV	HHV^{1P}	HHV^{2P}	HHV^{3P}	HHV^{4P}	HHV^{5P}	HHV^{6P}	HHV^{CP}
Cotton stalks	17.4	18.93	18.52	20.05	17.87	18.51	18.42	17
Sugar cane Bagasse	18.11	19.07	19.02	20.23	18.04	18.25	19.2	17.74
Rice husk	14.4	16.12	15.86	17.23	15.37	17.53	14.94	14.45
Rice straw	12.1	17.4	17.31	18.55	16.54	17.78	16.91	16
Wood chips	17.4	19.28	19.14	20.43	18.21	18.39	19.33	17.79
Neem wood	20.26	17.68	19.18	18.98	16.97	16.51	19.9	18.94
Mango wood	18.17	17.34	18.91	18.65	16.68	16.35	19.58	18.72
Eucalyptus wood	17.84	19.25	19.22	20.42	18.2	18.29	19.47	17.94
Sagoon wood	17.41	17.28	18.01	18.5	16.52	17.04	18.1	17.25
Mustard stalks	17.49	17.1	16.17	18.16	16.17	18.41	15.13	14.3

Table 4.4: Comparison with other Equations from the Literature and new correlation

Biomass	HHV	HHV^{1U}	HHV^{2U}	HHV^{3U}	HHV^{4U}	HHV^{5U}	HHV^{CU}
Cotton stalks	17.4	18.23	17.4	17.23	17.4	17.68	19
Sugar cane Bagasse	18.11	18.82	18.17	18.04	18.25	18.06	18.05
Rice husk	14.4	15.83	15.13	14.91	14.78	16.04	13.7
Rice straw	12.1	17.34	16.9	16.76	16.76	17.08	12.47
Wood chips	17.4	19.44	18.95	18.99	19.15	19.3	18.2
Neem wood	20.26	19.84	19.55	19.44	19.7	19.19	19.9
Mango wood	18.17	19.19	18.49	18.42	18.65	18.53	18.04
Eucalyptus wood	17.84	19	18.07	18.04	18.25	18.46	17.98
Sagoon wood	17.41	17.11	15.37	15.24	15.41	16.41	17.3
Mustard stalks	17.49	17.53	18.57	18.41	18.19	18.22	17.33

A lower AAE means a smaller error of the correlation. A positive ABE value implies an overall overestimation while a negative value means an overall under estimation. Smaller the value of ABE, the smaller will be the bias in the correlation. A correlation with a higher R^2 value makes a better estimation. The above three parameters are fundamental statistical criteria used widely in the error analysis, and also have been used to assess the fuel heating value correlations. Therefore they are adopted here also as the evaluation parameters. The values of the three parameters for all the correlations are calculated and also listed in Table 4.5, 4.6 & 4.7 for proximate and Table 4.8,4.9 & 4.10 for ultimate analysis correlations.

Table 4.5: Absolute Average Error for Different Correlation

All ten biomass fuels	ABE values(%) from different equations					
	AAE^{1P}	AAE^{2P}	AAE^{3P}	AAE^{4P}	AAE^{5P}	ABE^{CP}
	6.03	6.25	7.02	6.25	11.40	1.93

Table 4.6: Average Bias Error for Different Correlation

All ten biomass fuels	ABE values(%) from different equations					
	ABE^{1P}	ABE^{2P}	ABE^{3P}	ABE^{4P}	ABE^{5P}	ABE^{CP}
	5.24	5.18	3.41	5.18	10.14	-0.69

Table 4.7: Correlation Coefficient for Different Correlation

All ten biomass fuels	R² values from different equations					
	I	II	III	IV	V	NC
	0.91	0.91	0.46	0.86	0.51	0.94

Table 4.8: Absolute Average Error for Different Correlation

All ten biomass fuels	AAE values(%) from different equations					
	AAE^{1U}	AAE^{2U}	AAE^{3U}	AAE^{4U}	AAE^{5U}	AAE^{CU}
	1.8	4.6	3.9	3.9	5.5	1.28

Table 4.9: Average Bias Error for Different Correlation

All ten biomass fuels	ABE values(%) from different equations					
	ABE^{1U}	ABE^{2U}	ABE^{3U}	ABE^{4U}	ABE^{5U}	ABE^{CU}
	-0.29	2.1	0.79	0.40	4.8	0.19

Table 4.10: Correlation Coefficient for Different Correlation

All ten biomass fuels	R² values from different equations					
	I	II	III	IV	V	NC
	0.88	0.92	0.84	0.94	0.78	0.98

The values of average absolute and bias error with the new derived correlations are minimum compared to other while the value of correlation coefficient is the maximum. With these minimum values of average absolute and bias error as 1.93 and -0.69%, and maximum value of correlation coefficient 0.94 respectively for proximate analysis and 1.28, 0.19 & 0.98 for ultimate analysis the validity and merits of the proposed correlation stands established.

4.1 PARTICLE SIZE DISTRIBUTION

The Rosin-Rammler (RR) and Gates-Gaudin-Schuhmann (GGS) mathematical models applied to data obtained by sieve analysis of cotton stalks is represented in Fig. 4.1 & 4.2.

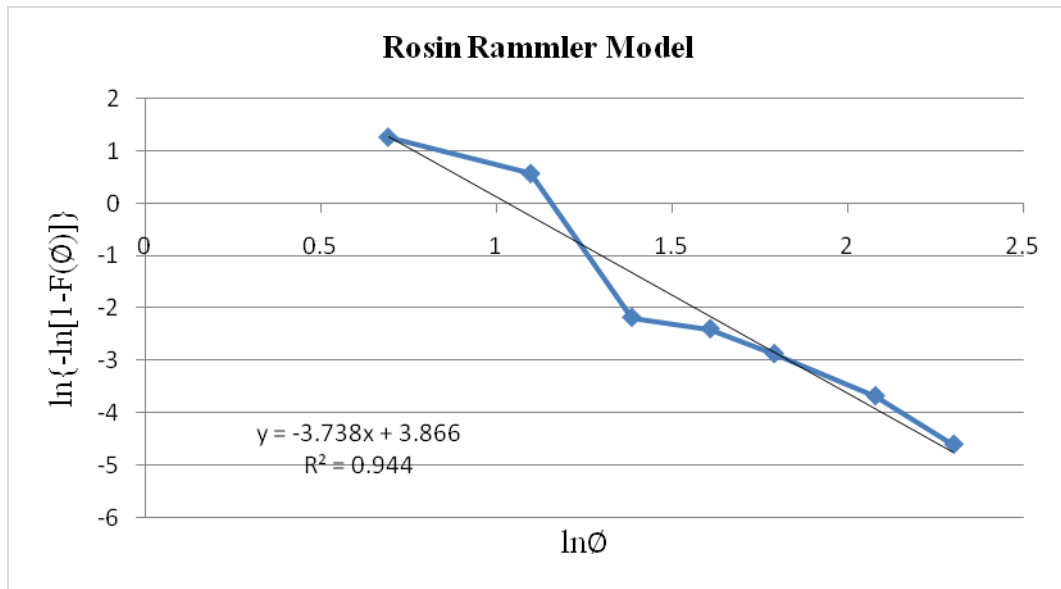


Fig 4.1: Rosin Rammler model on sieve analysis of cotton stalks

The correlation coefficient in Fig 5.1 is 0.944 whereas in Fig 4.2 it was 0.725 hence the cotton stalks data is following the Rosin-Rammler model and the resulting distribution functions obtained by application of RR model is given by the following expressions:

$$F(\phi) = 1 - \exp\left[-\left(\frac{\phi}{1.03}\right)^{3.74}\right] \tag{4.6}$$

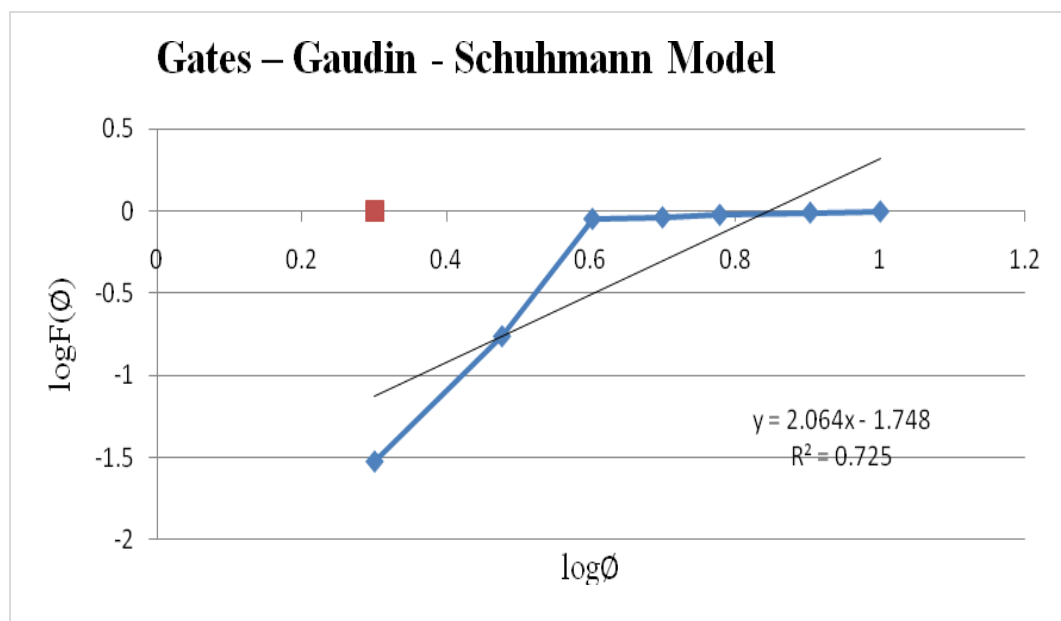


Fig 4.2: Gates Gaudin Schuhmann model on sieve analysis of cotton stalks

Size modulus and distribution modulus together provides description of particle size distribution. Size modulus represents the relative size of the sample, but it is not directly related to the average particle size of the sample. The distribution modulus is 3.74 which give

the idea of narrow distribution and the gasifier didn't produce any gas using this PSD of cotton stalks in the gasifier. As after crushing particle size of cotton stalk reduced to 4mm which is below the standard fixed for fixed bed gasifiers as proper gasification not take place due to reduction in surface area and volume. The fine particles of the cotton stalks blocked the flow of air introduction and creating agglomeration in the gasifier which overall results in stopping of gasifier and no gas production. Similar problem was reported by **Yin et al (2012)** and **Luo et al (2009)**.

To overcome this problem the cotton stalks are manually crushed into small size and again PSD of cotton stalks be evaluated. During manual crushing it was disintegrate into two different sizes of 10mm and 15 mm size.

Table 4.11: PSD analysis of cotton stalks (manual for 10 mm)

Range of Sieve Size (mm)	Mesh Size, \emptyset (mm)	Mass retained (gms)	Mass retained (%)	Cumulative mass	
				Oversize (%)	Undersize (%)
-9 + 10	8	4	4.04	4.04	95.96
- 10 + 9	9	5	5.05	9.09	90.91
- 11 + 10	10	42	42.42	51.52	48.48
- 12 + 11	11	15	15.15	66.67	33.33
- 13 + 12	12	18	18.18	84.85	15.15
- 14 + 13	13	12	12.12	96.97	3.03
+ 14	14	3	3.03	100.00	0.00

Table 4.12: PSD analysis of cotton stalks (manual for 15 mm)

Range of Sieve Size (mm)	Mesh Size, \emptyset (mm)	Mass retained (gms)	Mass retained (%)	Cumulative mass	
				Oversize (%)	Undersize (%)
-14 + 13	13	2	2.02	2.02	97.98
- 15 + 14	14	7	7.07	9.09	90.91
- 16 + 15	15	52	52.53	61.62	38.38
- 17 + 16	16	19	19.19	80.81	19.19
- 18 + 17	17	11	11.11	91.92	8.08
- 19 + 18	18	5	5.05	96.97	3.03
+ 19	19	3	3.03	100.00	0.00

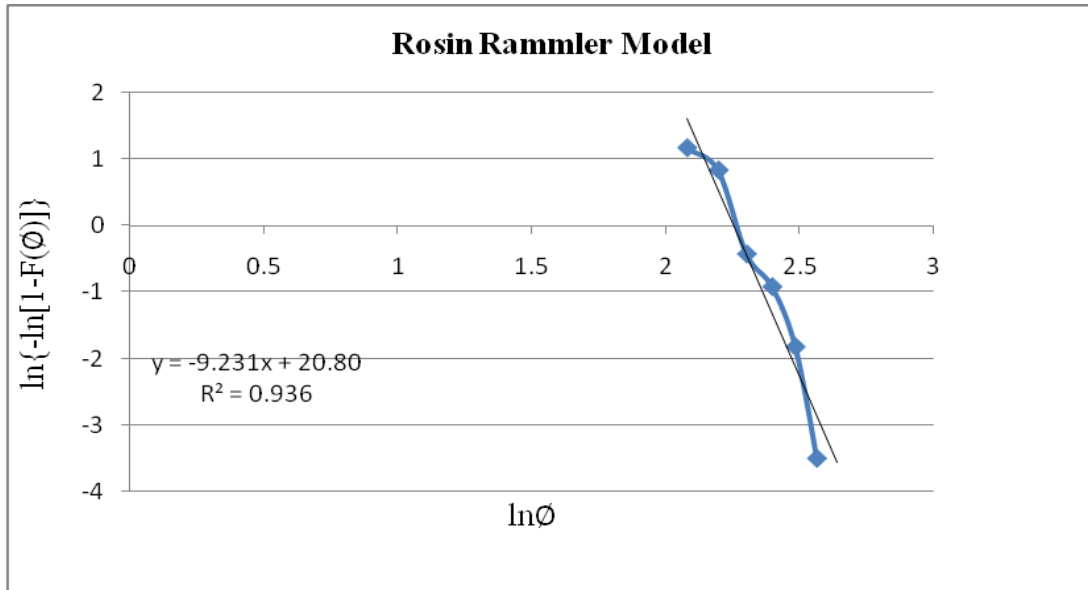


Fig 4.3: Rosin Rammler model on cotton stalks of 10mm size

Average particle diameter for cotton stalk has been found using the Rosin–Rammler equation. The Rosin–Rammler distribution function $F(\phi)_{10}$ is given by the following expression:

$$F(\phi)_{10} = 1 - \exp\left[-\left(\frac{\phi}{2.21}\right)^{9.23}\right] \tag{4.7}$$

The value of size modulus is input parameter for the model. Larger value of distribution modulus (9.23) is due to the wide-size particle distribution of cotton stalk. For a given size modulus, the smaller the value of the distribution modulus, the larger is the particle size distribution and vice versa.

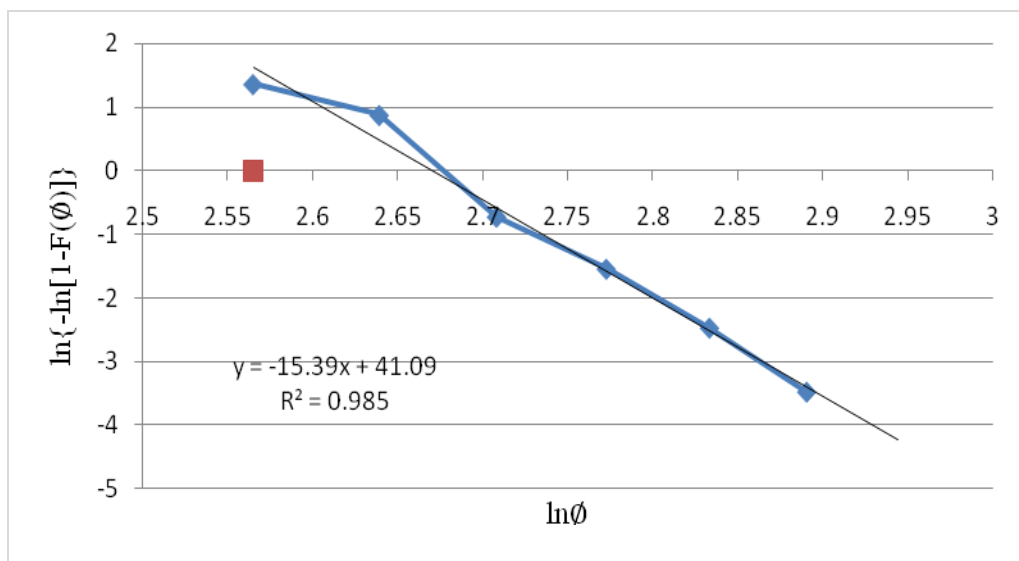


Fig 4.4: Rosin Rammler Model on cotton stalks of 15mm size

Average particle diameter for cotton stalk has been found using the Rosin–Rammler equation. The Rosin–Rammler distribution function $F(\phi)_{15}$ is given by the following expression:

$$F(\phi)_{15} = 1 - \exp\left[-\left(\frac{\phi}{2.66}\right)^{15.39}\right] \quad (4.8)$$

Larger value of distribution modulus (15.39) is due to the wide-size particle distribution of cotton stalk. For a given size modulus, the smaller the value of the distribution modulus, the larger is the particle size distribution and vice versa.

It was reported in literature that carry-over rate is high when distribution modulus is smaller. This attributes to the fact that smaller value of distribution modulus indicates wider particle size distribution, which means numbers of elutriable fines in the bed will be more. This results in higher carry-over rate. With high carry-over rate, the number of particles available for combustion decreases, leading to decrease in combustor efficiency.

In both the case of manual crushing of cotton stalks the distribution modulus is large which indicates the narrow particle size distribution and lower carry over rate and hence leads to higher combustor efficiency. Particle size is one of the important parameter affecting the composition, quality and final application of producer gas. Also, particle size and shape determines the difficulty of fuel feeding as well as its behaviour inside the downdraft gasifier. Varying particle size affects the heat release and flow of gas which in turn affects the performance and emissions levels of dual fuel engine.

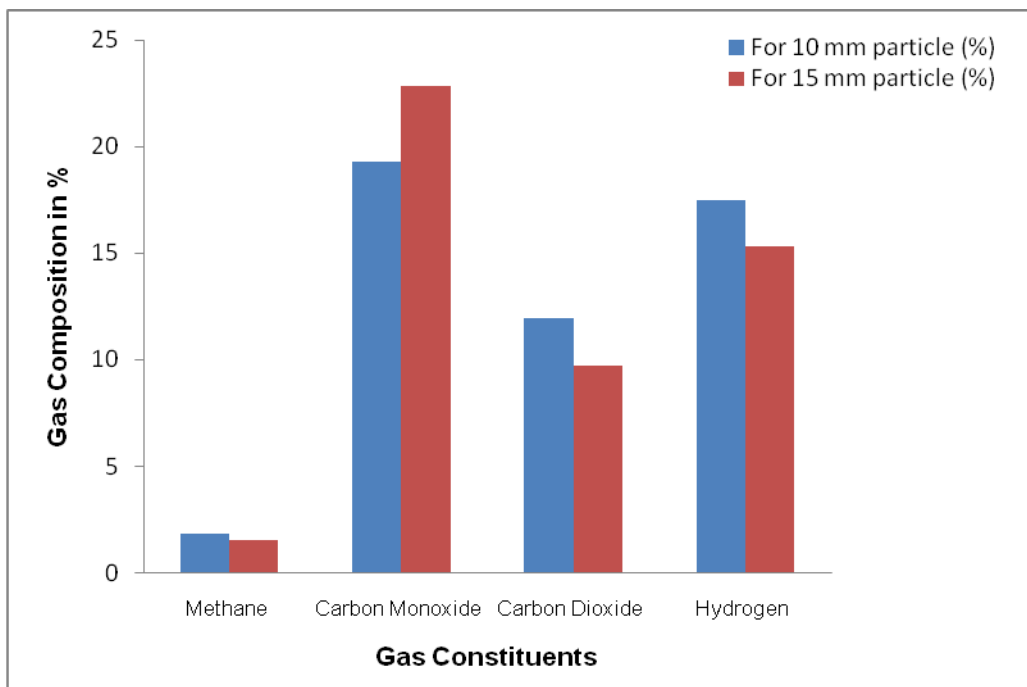


Fig 4.5: Composition of gas produced from gasifier at different PSD

The results obtained are similar to results reported by **Yin et al (2012)** and **Luo et al (2009)** where by increasing the particle size the composition of methane, carbon dioxide and hydrogen are decreasing whereas the carbon monoxide level is increasing.

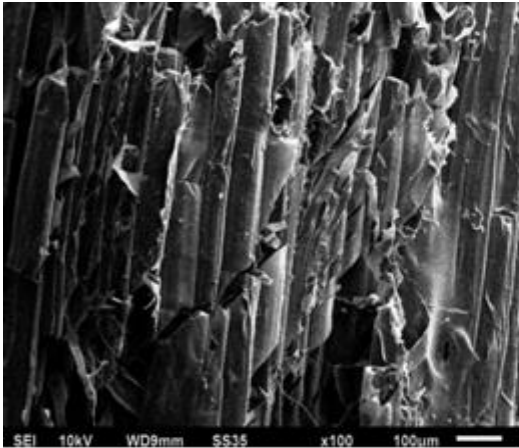


Fig.4.6: SEM images of sugarcane bagasse

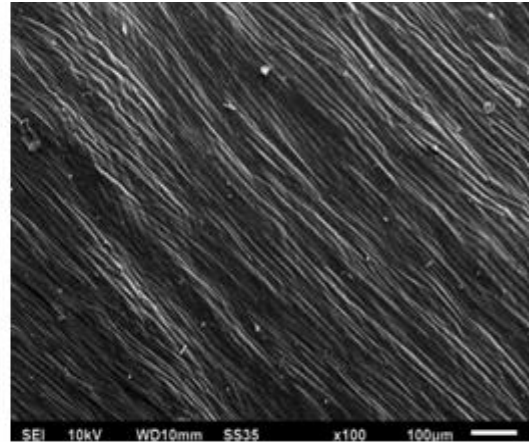


Fig.4.7: SEM images of cotton stalks

The SEM image of cotton stalks also justify the PSD problem occurred during crushing as it shows very thin long needle shape structure whereas bagasse has thick spongy structure.

4.2 GASIFIER PERFORMANCE

4.2.1 Specific gas production - Gas to Fuel Ratio (G/F)

In order to determine the Producer Gas to Fuel Ratio (G/F) carbon balance is used.

Using Carbon balance;

$$C_f = C_g + C_{c-a} + C_t \quad (4.9)$$

C_f = Rate of carbon input to the gasifier with fuel

C_g = Rate of carbon leaving the gasifier with producer gas

C_{c-a} = Rate of carbon leaving the gasifier with char-ash

C_t = Rate of carbon leaving the gasifier with tar

Assuming carbon in char-ash and tar is negligible compared to carbon in the producer gas;

$$C_f = C_g \quad (4.10)$$

Mass percentage of carbon in dry fuel wood is taken as 52.2% (FAO, 1986).

$$C_f = 0.522 F \quad (4.11)$$

F = Fuel consumption rate (kg/h)

From (4.10) and (4.11);

$$C_g = 0.522 F \quad (4.12)$$

Volumetric fraction of carbon in the producer gas is computed as follows:

$$C_{gv} = \sum \frac{\text{Vol. fraction of C containing component} * \text{Density} * \text{C weight per mole}}{\text{Molecular weight of component}}$$

Table 4.13: Producer gas component and C_{gv} calculations for 10mm PSD

Component	%	Density	C weight	Molecular weight	Vol. fraction of carbon in gas, C_{gv}
CH ₄	1.8	0.717	0.012	0.016	0.010
CO	19.3	1.25	0.012	0.028	0.103
CO ₂	11.92	1.977	0.012	0.044	0.064
H ₂	17.46	--	--	--	--
N ₂	49.52	--	--	--	--
				Total	0.177

$$C_{gv} = 0.177$$

$$C_g = C_{gv}G \quad (4.13)$$

G = Producer gas flow rate (m³/h)

From (4.13) and (4.13);

$$0.522 F = C_{gv}G$$

$$\left(\frac{G}{F}\right) = \frac{0.522}{C_{gv}} \quad (4.14)$$

$$\left(\frac{G}{F}\right) = \frac{0.522}{0.177} = 2.949$$

4.2.2 Specific air consumption - Air to Gas Ratio (A/G)

In order to determine the Air flow to Gas flow (A/G) nitrogen balance is used.

Using Nitrogen balance

$$N_F + N_a = N_g \quad (4.15)$$

N_F = Rate of nitrogen input to the gasifier with fuel

N_a = Rate of nitrogen input to the gasifier with air

N_g = Rate of nitrogen input to the gasifier with gas

Assuming nitrogen in fuel is very small compared to the nitrogen in air;

$$N_a = N_g \quad (4.16)$$

Taking volumetric fraction of nitrogen in air as 0.79;

$$N_a = 0.79 A \quad (4.17)$$

where A= Supply air flow rate (m³/h)

From (4.16) and (4.177);

$$N_g = 0.79 A \quad (4.18)$$

Volumetric fraction of nitrogen in the gas is obtained from the gas composition.

$$N_g = N_{gv}G \quad (4.19)$$

From (4.18) and (4.19);

$$0.79 A = N_{gv}G$$

$$\left(\frac{A}{G}\right) = \frac{N_{gv}}{0.79} \quad (4.20)$$

$$\left(\frac{A}{G}\right) = \frac{0.49}{0.79} = 0.627$$

4.2.3 Equivalence Ratio (ER)

Equivalence Ratio reflects the combined effect of air flow rate and fuel flow rate. This is defined as the ratio of operating air-fuel ratio to Stoichiometric air-fuel ratio.

$$ER = \frac{\text{Actual } \left(\frac{A}{F}\right)_o}{\text{Stoichiometric } \left(\frac{A}{F}\right)_s} \quad (4.21)$$

$$\left(\frac{A}{F}\right)_o = \frac{\text{Mass flow rate of air}}{\text{Fuel wood consumption rate}} = \left(\frac{A}{G}\right) \left(\frac{G}{F}\right) * \text{Density of Air} \quad (4.22)$$

Stoichiometric air-fuel ratio is taken as 6.36 kg of air per kg of wood (SERI, 1988)

Density of Air = 1.245 kg/m³

$$\left(\frac{A}{F}\right)_o = \left(\frac{A}{G}\right) \left(\frac{G}{F}\right) * \text{Density of Air} = 0.627 * 2.949 * 1.245 = 2.302$$

$$ER = \frac{\text{Actual } \left(\frac{A}{F}\right)_o}{\text{Stoichiometric } \left(\frac{A}{F}\right)_s} = \frac{2.302}{6.36} = 0.362$$

4.2.4 Lower Heating Value of Gas

Lower Heating value (LHV) of producer gas is determined from the chemical composition of the gas and LHV of individual components.

$$(LHV)_{gas} = \sum \text{volume \% of component} \times \text{LHV of the component} \tag{4.23}$$

Table 4.14: LHV of each component calculation for 10 mm PSD

Component	%	C.V. (kJ/m ³)	Vol. Fraction C.V.
H ₂	17.46	10788	1883.58
CH ₄	1.8	35814	644.65
CO	19.3	12622	2436.05
CO ₂	11.92		0
C.V. of gas(kJ/m³)			4964.28

$$(LHV)_{gas} = 4.964 \text{MJ/m}^3$$

Hence for different particle size distribution the gasification parameters are calculated as:

Table 4.15: Gasification Parameters

	for 10mm particle size	for 15mm particle size
Gas to Fuel Ratio	2.949	2.868
Air to Gas Ratio	0.627	0.642
Gas Flow Rate	11.2 m ³ /hr(In Engine)	11.2 m ³ /hr(In Engine)
Equivalent Ratio (ER)	0.362	0.360
Lower Heating Value of Gas	4.964 MJ/m ³	5.073 MJ/m ³

The ash composition also plays an important role in gasification. Table 4.16 includes the ash composition which was produced in gasifier.

Table 4.16: Ash Composition

Element/Gas	Amount (%)
K_2O	0.4
CaO	1.3
SiO_2	0.3
Cl	0.4
P_2O_5	0.06
Fe_2O_3	0.8
MgO	0.1

Most of the chlorine is released as HCl into the gas phase. Consequences are corrosion in engine but the value of chlorine is significantly low which prevents the chances of corrosion in engine. The lower value of potassium also reduces the chances of ash becomes sticky and increases the risk of reactor slagging.

4.3 COMBUSTION

In-cylinder pressure data of engine were analyzed for rates of heat release, mass fraction burned and mean gas temperatures with respect to crank angle for diesel fuel and twin fuel of producer gas-diesel mixture fuel.

4.3.1 Mass Fraction Burned vs. Crank Angle:

The mass fraction burned was obtained by integrating the rate of heat release. The curve of the mass fraction burned with respect to crank angles represents the identification of ignition delay, the fully developed combustion period and the combustion tail. Also, it gave information about unburned fuel at any point in the combustion cycle. Representative curves for the mass fraction burned for the diesel fuel and producer gas-diesel mixture fuel with respect to crank angles at 1500 rev/min engine speeds are shown in Fig. 4.8 and 4.9, respectively. The burn duration and ignition delay in terms of crank angles for diesel fuel and producer gas-diesel mixture fuel are quantified in these figures. Four points defined in those curves are the start of combustion, 10 % of combustion, 50 % of combustion and 90% of combustion. Although ignition delay is technically defined as the interval between the start of injection and start of combustion but to assess mass burned fraction from engine cycle analysis, the 0 to 10 % burned range is often defined as the ignition delay and the 10 to 90% range is the burn duration.

The last 10 % burned is not usually considered due to errors associated with the assumptions made in the heat-release analysis. The quantification of these parameters is extremely beneficial in characterising combustion chamber and ignition system performance. The ignition delay period in a CI engine is a very important performance parameter that influences subsequent combustion processes, engine performance and exhaust emissions. The variations of ignition delay with the different crank angle for different fuels in single and dual fuel mode of operation in a diesel engine is shown in Fig. 4.8 & 4.9.

Ignition delay period in dual fuel mode is longer than the pure diesel fuel operation due to the reduction in the intake oxygen concentration, resulting from producer gas inducted along with intake air and partly due to the change in the specific heat of the compressed mixture that resulted in lowering the compression temperature. Primary fuel occupying in compression process undergoes chemical pre-ignition reactions leading to primary ignition delay where the pressure starts to decrease in this period and its rate is very low.

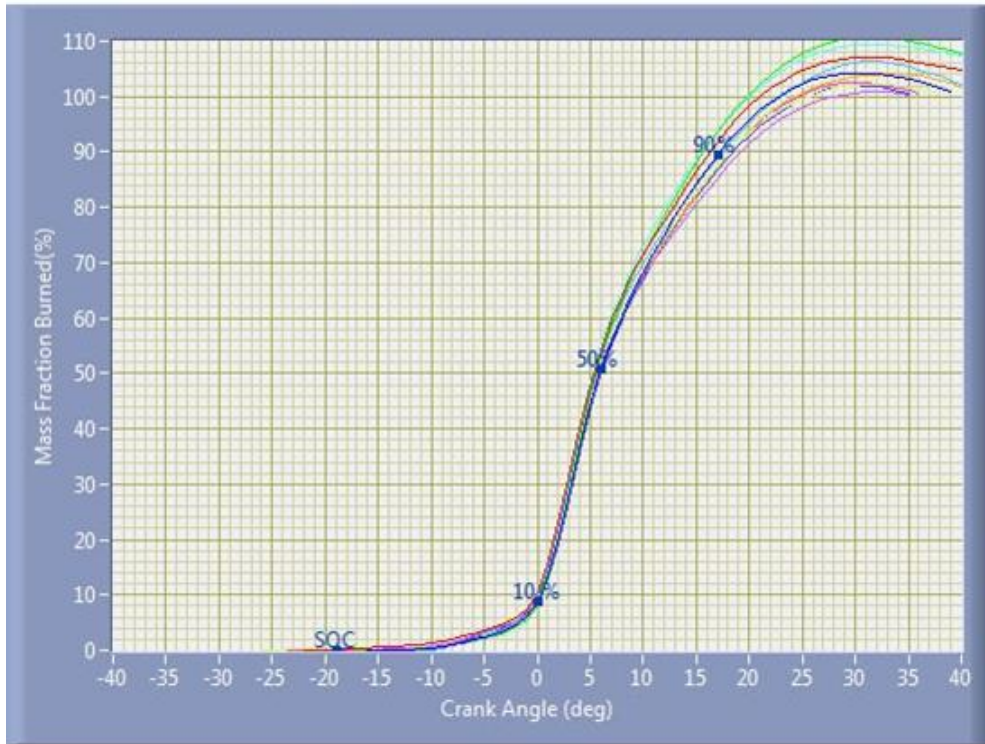


Fig.4.8 Mass fraction burned of Diesel at different crank angle positions

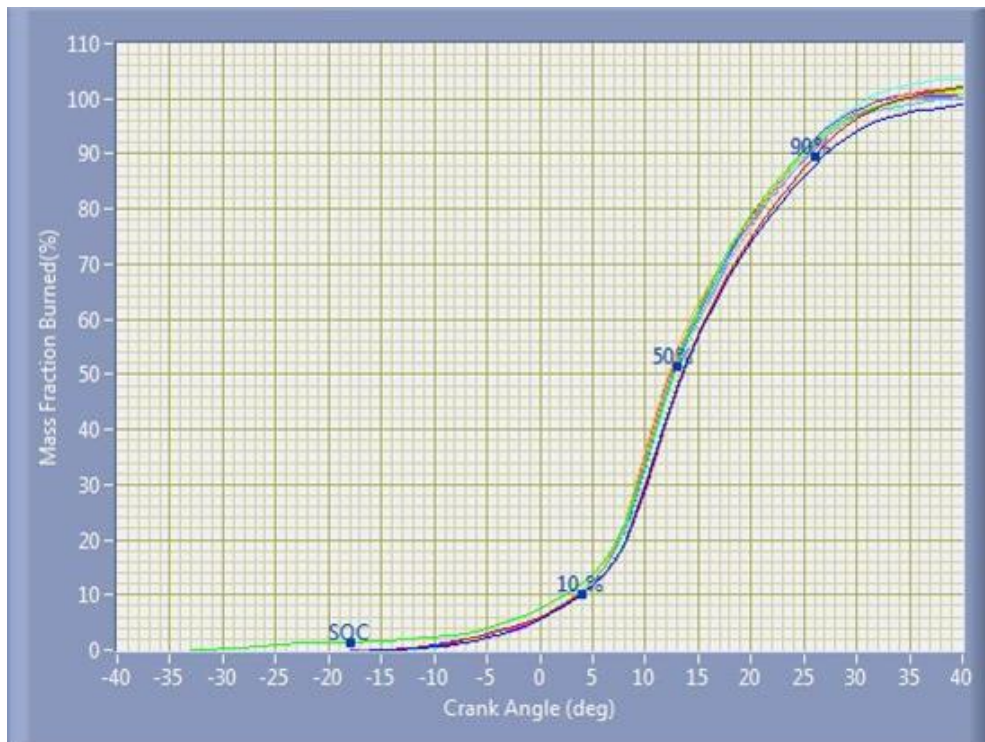


Fig.4.9 Mass fraction burned of Producer gas-Diesel at different crank angle positions

In dual fuel mode operation of the engine, the admission of a gaseous fuel with the air influenced intensely both the physical and chemical ignition processes of the mixture. Its introduction would bring variations in the physical properties of the mixture such as the specific heat ratio and heat transfer parameters. These could lead to drastic changes in the

charge temperature and pressure levels at the time of fuel injection and extend the physical ignition delay period of the mixture.

Ignition delay depends on temperature, fuel injection pressure, fuel properties and turbulence. Longer ignition delay is observed with mixed fuel mode due to the producer gas slow burning nature. It is observed that the ignition delay of 22° with dual fuel mode was 3° more than the single diesel fuel mode of operation.

When compared to diesel fuel combustion, the ignition delay for dual fuel combustion was prolonged with the lower peak combustion pressure as shown in Fig 4.10 & 4.11. The combustion process of a dual-fuel engine was more complicated than that of single-fuel. Prior to ignition of the pilot fuel, the gaseous fuel–air mixture underwent pre-ignition chemical reactions. The pre-ignition reactions resulted in the formation of active radicals and partial combustion products those were believed to affect the ignition of the injected pilot fuel [52]. Producer gas slow burning nature influences the ignition delay during uncontrolled combustion phase, which results in reduced peak pressure [116].

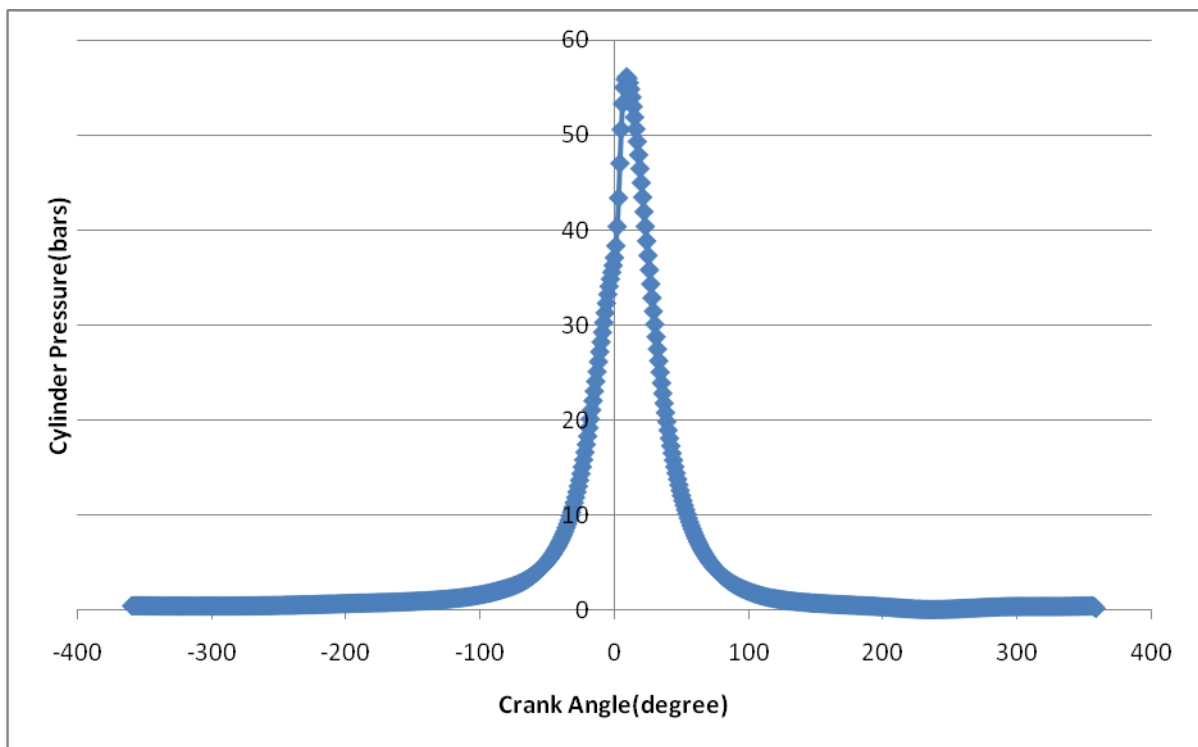


Fig.4.10 Cylinder Pressure in Diesel at different crank angle positions

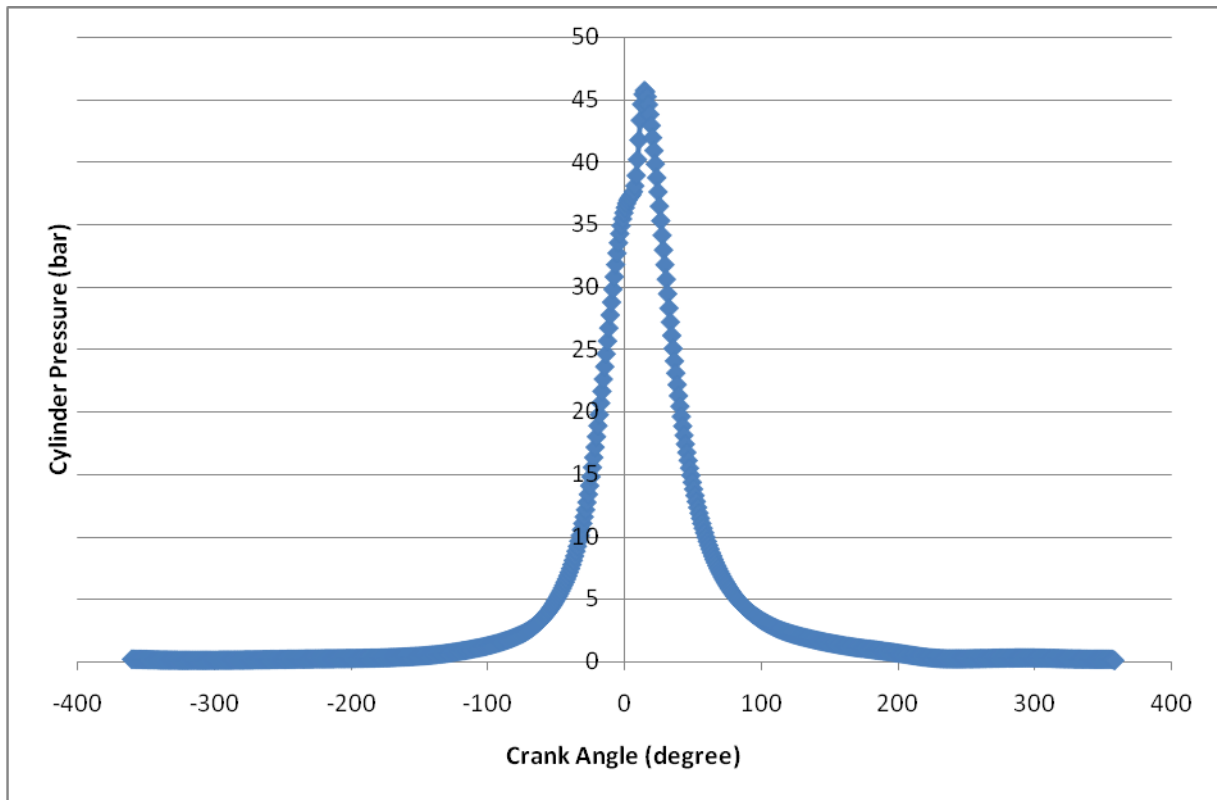


Fig.4.11 Cylinder Pressure in Producer gas-Diesel at different crank angle positions

It is observed that combustion duration during dual fuel mode of operation is higher than the single fuel mode of operation. Cylinder peak pressure mainly depends on the heat release rate of fuel inside the combustion chamber. The cylinder peak pressure is about 56.1 & 45.71 bars for diesel and dual-fuel of producer gas and diesel case respectively. For all the cases the peak pressure lies in between 9° and 15° crank angles after TDC. Dual fuel mode has higher pressure crank angle due to the time lag between the pilot fuel combustion and fumigated gas fuel combustion. The cylinder pressure under dual fuel operation decreases when increasing the amount of producer gas. It is mainly the due to the higher specific heat capacity of the producer gas-air mixture and its slower combustion rate compared to that of diesel fuel. Although, no danger exists for the engine structure due to these pressure changes. **Ali et al (1996)** , **Balakrishnan et al (2013)**, **Raheman and Radhee (2014)** reported the increase of 2° , 5° and 3° respectively in the crank angle due to ignition delay which is similar to the present experimental data. Also they reported the drop in cylinder pressure by 5-7 bar in case of dual fuel combustion.

4.3.2 Heat release rate (HRR) vs. Crank Angle:

The commencement of ignition, the mass proportion of fuel burned in the premixed manner, and differences in burning speed of fuels were recognized by heat release rate data. The rate of

heat release was lower in twin fuel combustion as compared to solo fuel combustion. The gaseous fuel with the intake air charge will decrease and dilute the oxygen concentration. Decrease of charge air temperature at the time of starting pilot injection is due to the lower polytropic index of producer gas and the pre-ignition reactions of the producer gas–air residual mixtures during the intake and compression processes. These principal factors might have caused ignition delay to extend [76].

A variation of gas pressure and temperature within the engine cylinder is caused due to the heat release rate of fuel. To obtain quantitative information on the progress of combustion in-cylinder gas pressure and crank angle data over the compression and expansion strokes of the engine operating cycle can be used. The mean cylinder pressure trace is estimated. From the above said data.

Fig. 4.11 and 4.13 show the effect of producer gas quantity on the cylinder pressure and the heat release rate for dual fuel mode of operation at constant speed and pilot diesel of 1500 rpm and 0.65 kg/h, respectively. It can be observed that combustion starts later for higher gas amount comparing to the diesel operation in Fig. 4.10 and Fig. 4.12. In a dual fuel engine, peak pressure depends on the combustion rate in initial stages, which in turn is influenced by the amount of fuel taking part in the premixed combustion phase. The premixed or uncontrolled combustion phase is governed by the ignition delay period and by the mixture preparation during the delay period. Thus, slow burning nature of producer gas during the ignition delay period is reasons for this trend of peak pressure. The ignition delay in dual fuel operation strongly depends on the type of gaseous fuel and their concentrations present in the cylinder charge.

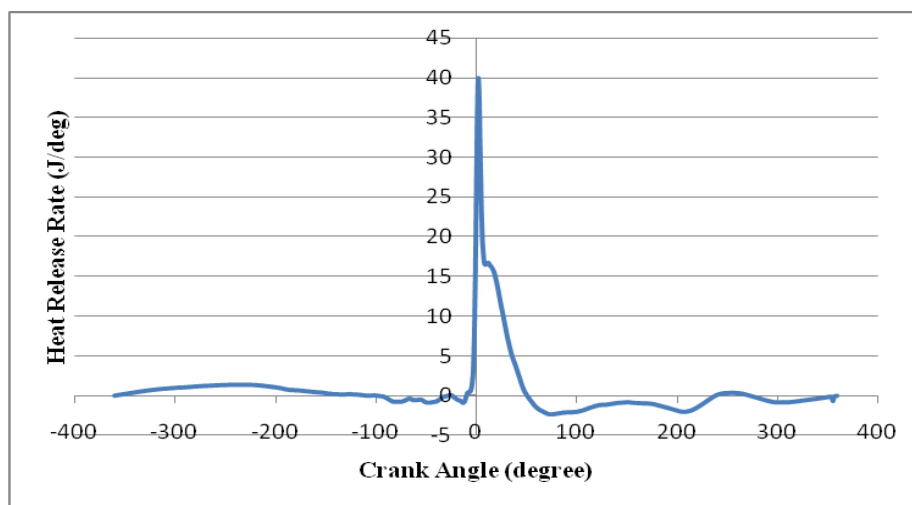


Fig.4.12 Heat Release Rate in Diesel at different crank angle positions

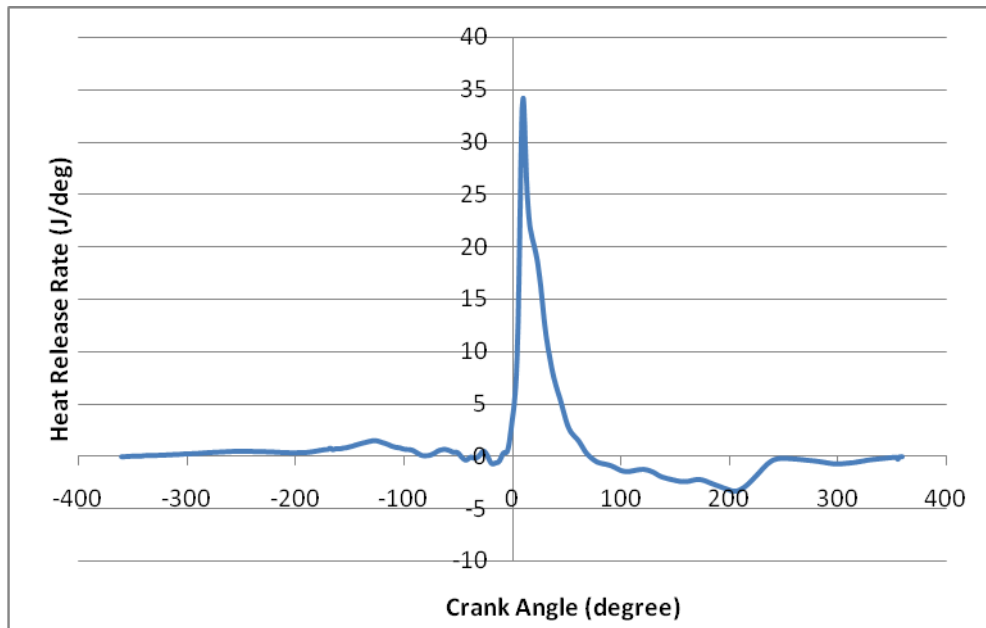


Fig.4.13 Heat Release Rate in Producer Gas-Diesel at different crank angle positions

The reason for increase in ignition delay is due to a large amount of producer gas fuel in the intake and compression process. The increase of the ignition delay period leads to a rapid increase of the total heat release curve during the premixed controlled combustion phase. This leads to improving the fuel conversion efficiency since the duration of combustion becomes shorter.

It has been reported in literature that with the higher amount of diesel, combustion of the gaseous fuel is better leading to elevated BTE as well as mass proportion burnt in twin mode as compared to the diesel only process. In the primary phase of combustion the heat is primarily released due to the premixed flaming of the pilot amount of diesel in accumulation to little part of gas entrained in the spray. In the next phase heat is produced by self ignition of gas-air blend in the close surrounding area of pilot diesel spray and diffusive flaming of the residual pilot fuel whereas in the last phase, the flaming of the gas-air blend by flame dissemination initiated from spray region are responsible for heat release. Similar trend of heat release rate was reported by **Raheman and Radhee (2014)**.

4.3.3 Mean Gas Temperature vs. Crank Angle:

Mean Gas temperature was observed from the measured pressure and volume data. This relationship estimated only the average temperature. Representative curves for mean gas temperature of diesel fuel and producer gas-diesel mixture fuel with crank angle at 1500 rev/min engine speed are shown in Figs. 4.14 and 4.15. The trends of temperature change for both fuels were similar. At 1500 rev/min, the mean gas temperature was 1200 °C for the fuels.

The respective locations of the peak mean gas temperatures for diesel and producer gas-diesel fuel were 22° and 27° crank angle after TDC. This is also demonstrated in the results obtained by **Ali et al (1996)**, **Balakrishnan et al (2013)**. They reported the 24° and 29° crank angle after TDC for 1300° C

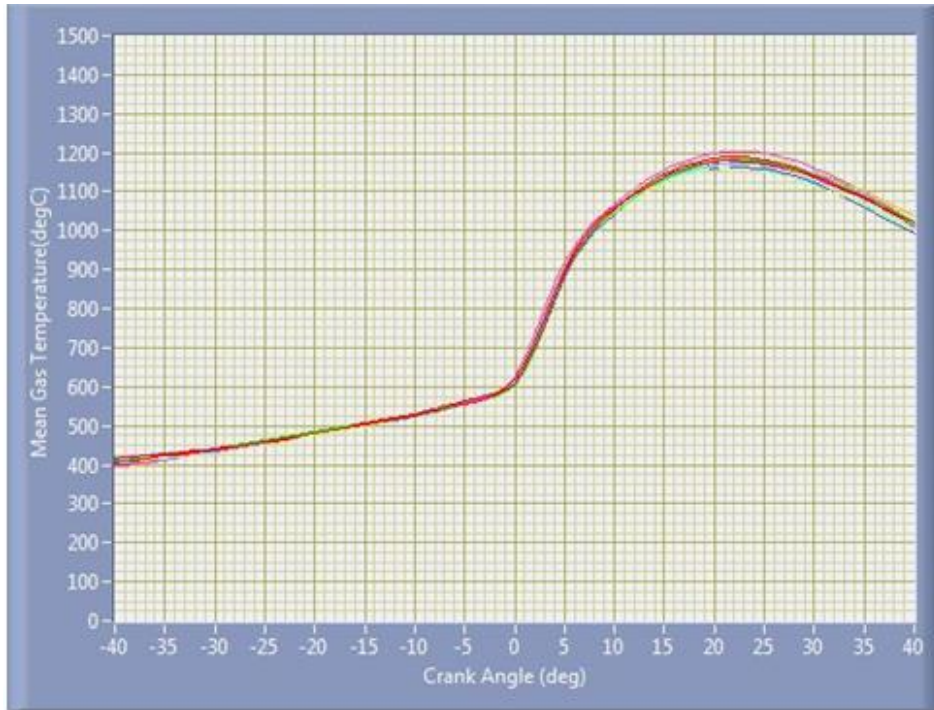


Fig.4.14 Mean gas temperature of Diesel at different crank angle positions

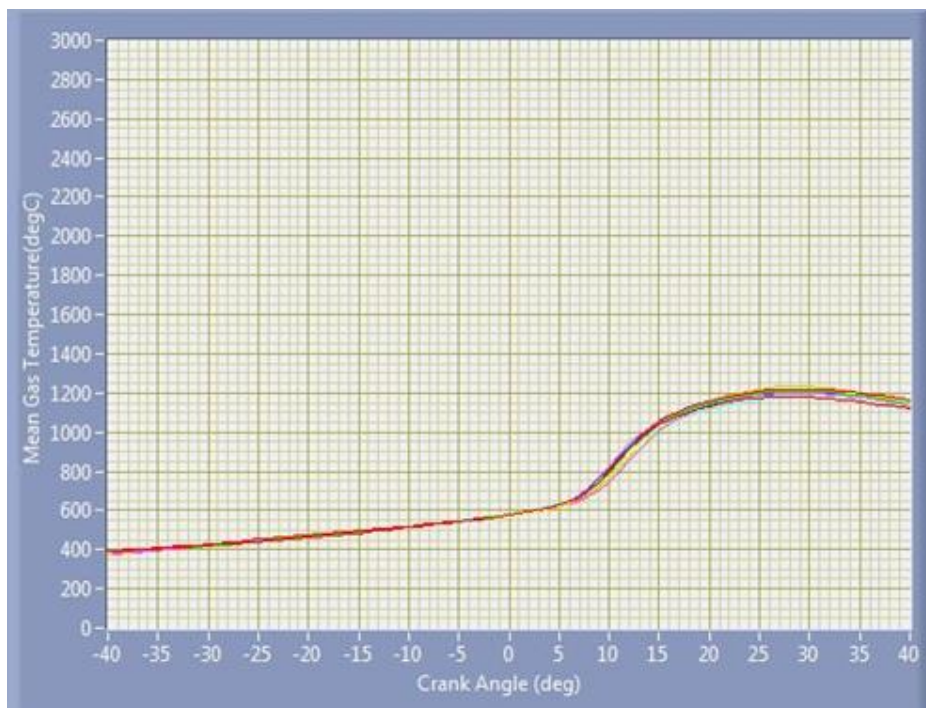


Fig.4.15 Mean gas temperature of Producer gas-Diesel at different crank angle positions

4.4 PERFORMANCE CHARACTERISTICS

It is clearly indicated that the brake thermal efficiency for twin fuel mode of operation is higher than the single fuel mode due to the higher amount of combustible gases present in producer gas generated from cotton stalks. Also, the producer gas from cotton stalks contains the suitable fraction of inert gases such as carbon dioxide and nitrogen, which affect the overall combustion process in the engine. The introduction of producer gas through the inlet manifold of the engine reduces the fresh air intake, which is a barrier to complete combustion. In addition to that more space is occupied by producer gas in combustion chamber results in less volumetric efficiency in twin fuel engine as compared to diesel fuel engine.

A substantial raise in BTE was found in twin fuel mode as compared to solo fuel mode at all loading conditions as shown in Fig 4.16. A maximum brake thermal efficiency of 24.02% was achieved in diesel mode, while in the twin fuel mode of operation the maximum brake thermal efficiency was of 43.05% at 10 kg load using cotton stalk. Ramdhas et al (2006) reported it around 25% for diesel and 19% for dual fuel mode due to lower calorific value of gas.

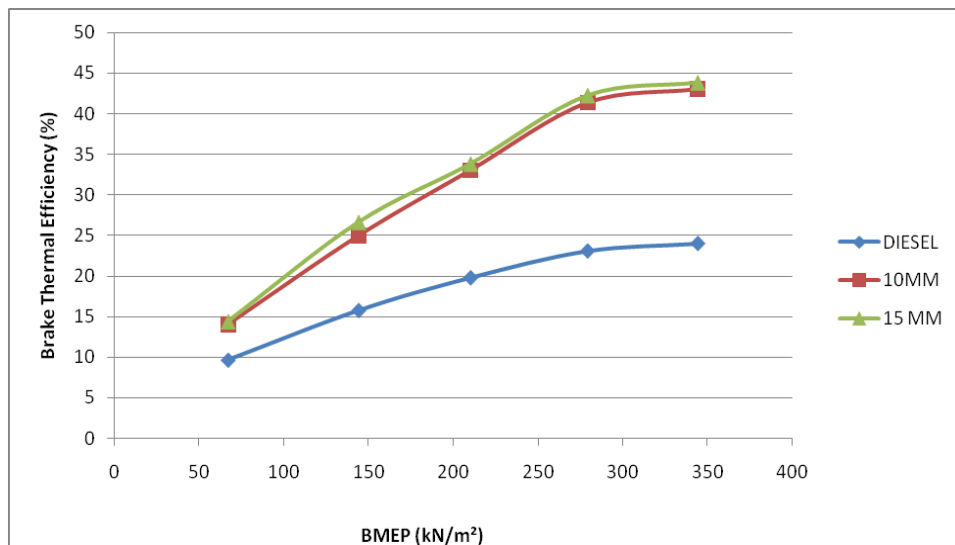


Fig.4.16: Brake thermal efficiency at different BMEP

This was due to the effect of the higher heating value of syngas, high combustible heat of left over gases and elevated total fuel flow speed during the combustion procedure. **Hanoka et al (2005)** also reported that cellulose type biomass have 35.5 % by vol. CO, 27 % by vol. CO₂ and 28.7 % H₂ in the producer gas obtained through it. The different sizes of particle distributions have no effect on the brake thermal efficiency as predicted from the figure. In the traditional IC engine, the supply of producer gas through the inlet manifold will contribute energy up to some extent. Obviously, the addition of producer gas will reduce liquid fuel in

internal combustion engine through governor mechanism used to regulate the liquid fuel. Fig 4.17 shows the effect of load on liquid fuel replacement in twin fuel mode and single fuel mode of operation. The proportion of diesel fuel utilization is greatly inferior in twin fuel mode than of diesel fuel mode for all loading situation, which represents the better combustion of producer gas and diesel in twin fuel mode.

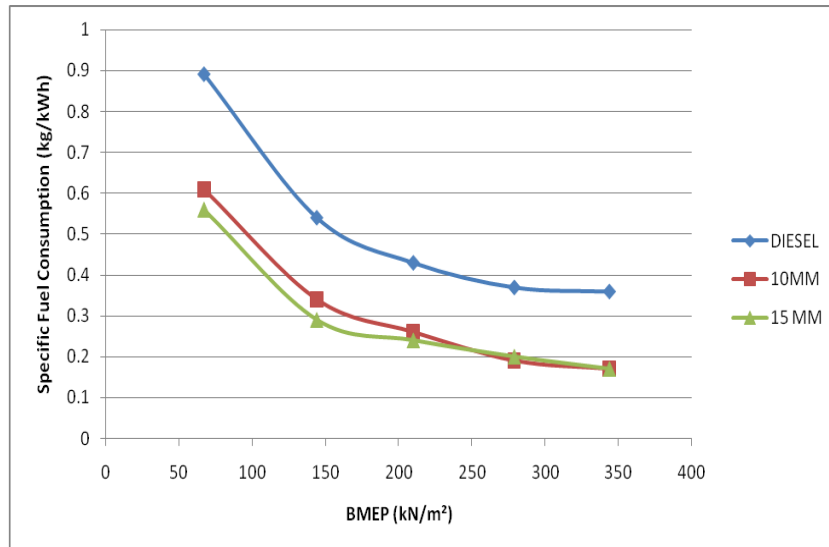


Fig.4.17: Specific fuel consumption at different BMEP

The proportion of savings using cotton stalk is higher than that of diesel (by 52%) throughout the operating range of the engine. At low load operation there is insufficient oxygen to complete combustion, which results in lower diesel saving. Liquid fuel replacement mainly depends on the injected fuel properties [11, 38, and 107]. Initially the larger particle size cottons stalk consumes less diesel as compared to other sample size cotton stalk but at higher load it was same diesel saving. **Uma et al (2004)** reported the diesel replacement of 67-86 % while **Ramdhas et al (2006)** reported it around 50%

The BSEC is much higher in twin fuel mode than that of diesel fuel mode for all load settings, which represents the more energy utilised during combustion of syngas and diesel in twin fuel mode. At low load operation there is insufficient oxygen to complete combustion, which results in higher brake specific energy consumption.

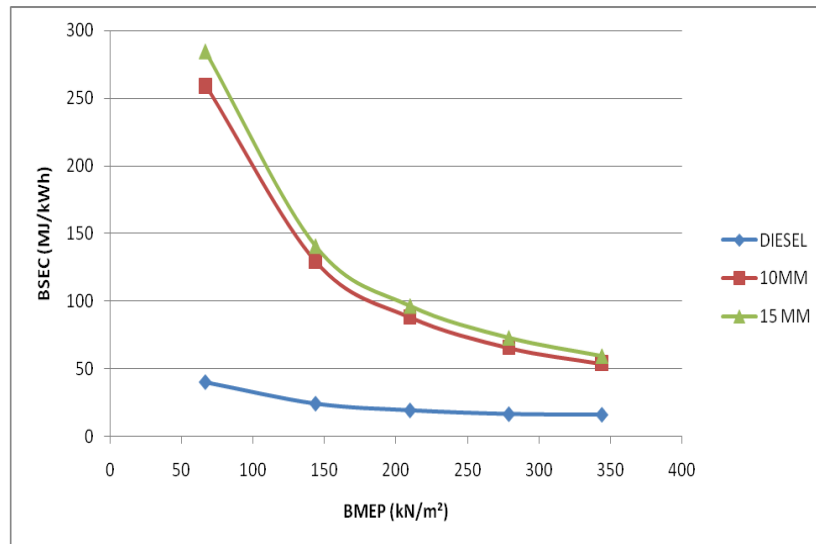


Fig.4.18: Brake specific energy consumption at different BMEP

4.5 EXHAUST EMISSIONS

The main reason for higher exhaust gas temperature is the excess energy supplied to the engine during twin and mixed fuel modes of operation.

The relationship between CO emissions and load is shown in Fig. 4.19 for both operating modes. Emission of CO is indicative of incomplete combustion in process. Emissions of CO are dependent on equivalence ratio, cylinder charge temperature and partially burned gaseous fuel. Observing Fig. 4.19, it is found that at fractional load escalating the quantity of gaseous fuel, leads to a quick enhancement of CO emissions level. It is also revealed that twin fuel operation suffers from high CO emissions, particularly at low loads. Diesel operations, on the other hand, produce low CO emissions. At low loads, dual fuel combustion is characterized by slower combustion rates compared to diesel, which results in lower cylinder charge temperature and poor quality combustion ensuing to a diminution of the oxidation process of CO. At intermediate loads, twin fuel combustion is improved with lower CO emissions compared to low loads. This declining trend continues at high loads. CO emissions are overall greater as compared to diesel operation. This higher emission at part load is due to the lower combustion temperature which in turn reduces the combustion efficiency.

The rate of CO formation is a function of combination of heat and existing quantity of unburned gaseous fuel, both of which control the speed of fuel disintegration and oxidation. The extent of diesel jet penetration is another factor that likely influences incomplete combustion and CO emissions at low loads. At low loads, the mass of diesel fuel injected is much smaller (about 40% reduction) than high load for twin fuel operation. When less mass is

injected the diesel jet penetration is not as great and less likely to extend throughout the combustion chamber. This reduces the probability of complete combustion of the entire air and producer gas mixture.

Carbon monoxide emission for dual fuel mode of operation is always much higher than the diesel only mode of operation. This is due to the supply of producer gas reduces the fresh air intake into the system, which in turn reduces oxygen to meet out the combustion process. The lower heating value and lower adiabatic flame temperature of producer gas also have their own impact.

It is also observed in literature that the increase of pilot fuel amount, keeping the engine load constant, leads to a decrease in CO emissions. A larger pilot fuel quantity provides a greater magnitude of ignition centres with large reaction zones. Also, the flame propagation path from each ignition centre within the charge becomes relatively shorter, and hence, combustion is better. At elevated loads, when the gaseous fuel content in the air mix is above the lean incineration limit, the flare is able to spread through most of the combustion chamber independently, and altering the pilot fuel amount has slight consequence. **Ramdhas et al (2006)** reported the rise of carbon monoxide by 250 % while **Uma et al (2004)** reported the rise of 300 % in carbon monoxide level in the dual fuel mode of operation.

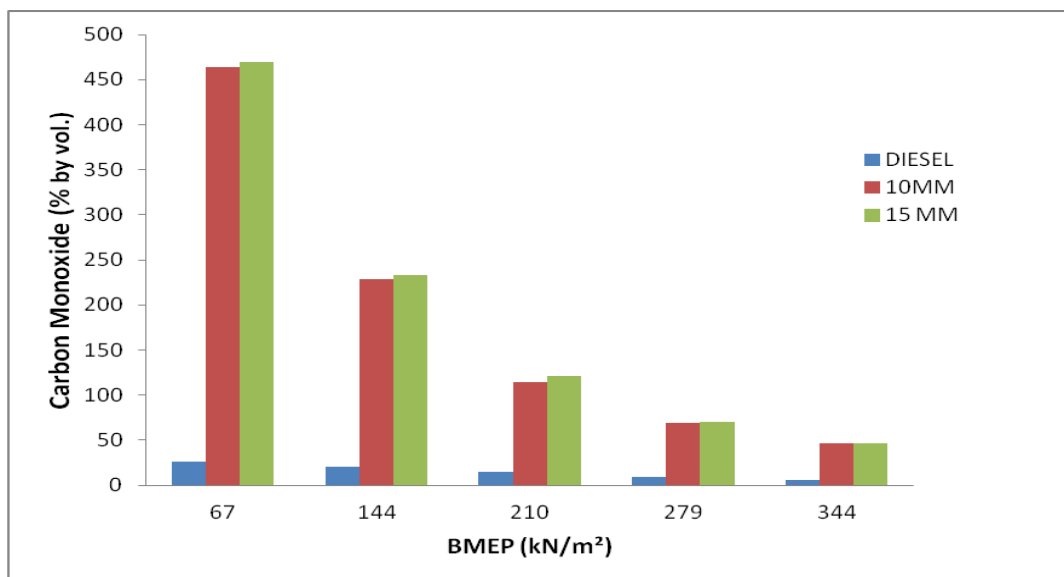


Fig.4.19: Carbon monoxide emissions at different BMEP

Fig. 4.20 shows the effect of load on smoke opacity for diesel and dual fuel mode of operation. Lower smoke opacity is observed with the dual fuel mode of operation compared with the single fuel modes of operation. Higher smoke opacity obtained with diesel is 3.5 %

while with dual fuel mode it was 2.7 %. However, the smoke opacity increases with the load for diesel as well as dual fuel modes of operation, which represents poor atomization characteristics, particularly at higher load condition. **Ramdhas et al (2006) and Singh et al (2005, 2007)** reported the reduction the reduction of smoke density by 35% and 24 % respectively. The different particle size distributions of cotton stalks have a negligible effect on exhaust emissions of carbon monoxide.

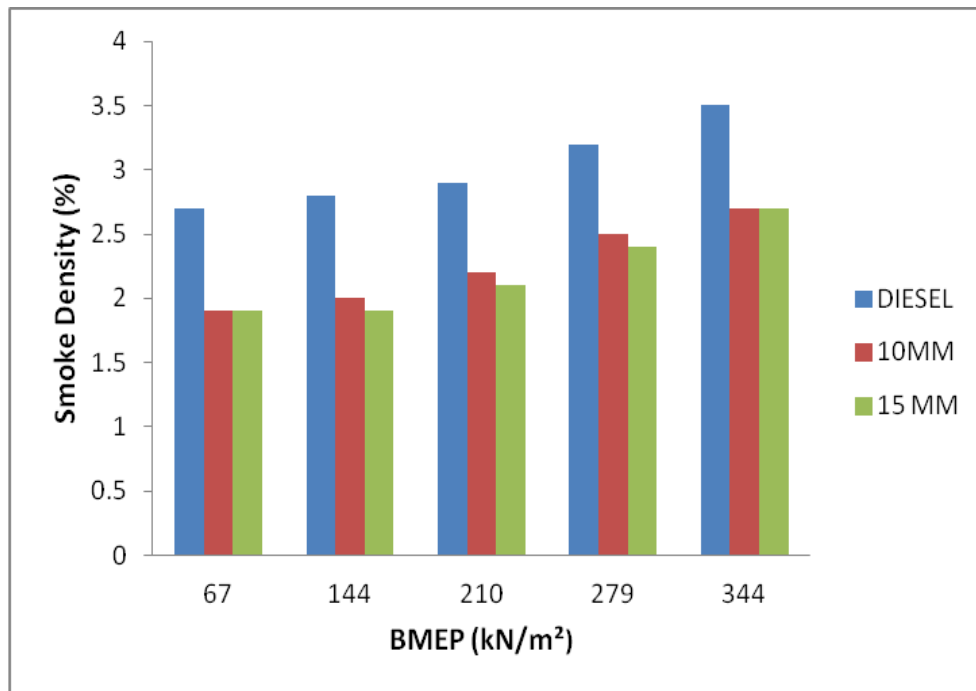


Fig.4.20: Smoke density emissions at different BMEP

Examining this figure gives an impression that twin fuel process is a probable way for dropping smoke emissions. At part load as the syngas mass ratio increases, the smoke content decreases drastically since fewer liquor fuels is injected into the engine on a proportion basis and thus a lesser amount of smoke is formed. But at elevated mass ratios smoke decreases and the decline compared to diesel process is sharper. This is maybe due to the elevated gas heat that promotes smoke oxidation speed contributing to an additional decrease of smoke content. The dissimilar sizes of particle distributions of cotton stalks have a negligible effect on exhaust emissions of smoke.

NO_x is the sum of NO and NO_2 . There are other oxides of nitrogen sometimes included, but they are insignificant in diesel and producer gas engines. Fig. 4.21 shows measured NO_x emissions at five loads for the two operating modes. The figure indicates that twin fuel operation emits less NO_x throughout the load map. NO_x formation is dependent on the oxidation of atmospheric nitrogen. The most significant component, NO_x is described by the

extended Zeldovich mechanism, which is strongly affected by cylinder charge temperature. In twin fuel operation, part of the combustion process occurs in the lean, premixed regime. For normal diesel operation, most of the fuel is burned as a diffusion flame near stoichiometric equivalence ratio. Stoichiometric combustion produces higher NO_x due to higher combustion temperatures.

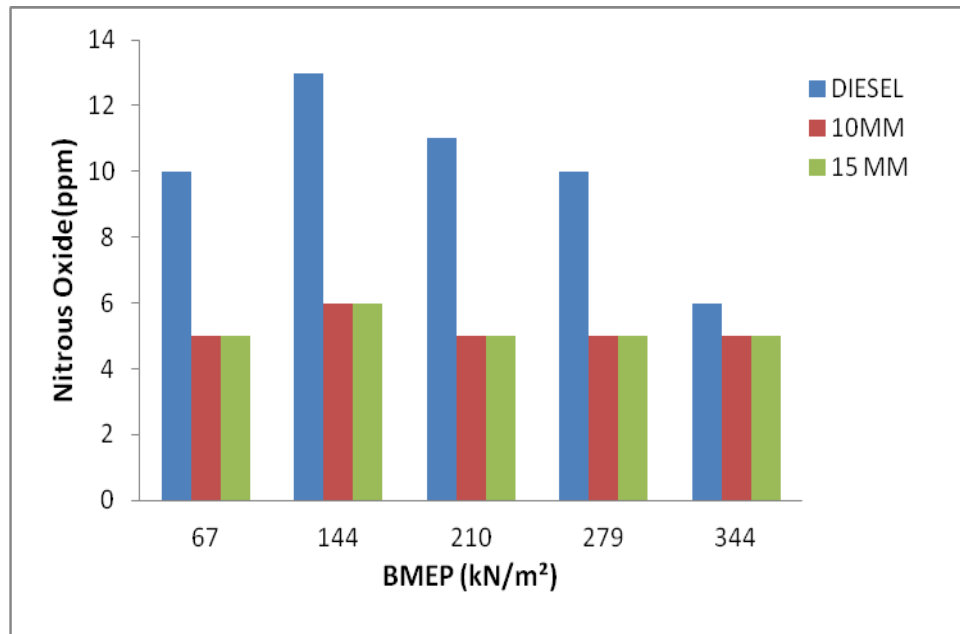


Fig.4.21: Nitrous oxide emissions at different BMEP

It appears that the same combustion and engine operating phenomena are affecting both operating modes. At low loads the 0-10% burn duration is higher and 10-90% burn duration is lower for twin fuel modes. Consequently, the premixed diesel combustion phase is more predominant, which produces more NO_x . This is more pronounced for diesel mode. It was also observed that the NO_x content in emission amplified at low load with a raise in engine load for all the fuels experimented. The standard gas temperature in the combustion chamber amplified as the engine load amplified which result in the augmentation of heat energy release from the fuel. This resulted in lower NO_x emissions at higher loads. The NO_x content in twin fuel mode process was found to be inferior to the diesel mode procedure because of the nonexistence of organic nitrogen from the air. The syngas had no crude nitrogen, it had only atmospheric nitrogen. **Uma et al (2004)** reported the reduction by 50% in NO_x level; **Singh et al (2005, 2007)** and **Wu et al (2003)** also reported the reduction by 45% and 35 % respectively in the emission levels of NO_x .

The probable justification for the decline of NO_x content, is the decline of gas heat due to augment of the specific heat ability, the less concentrated and slower premixed incineration,

and also the diminution of oxygen content due to existence of the syngas mass fraction, which replaces an equivalent quantity of air in the cylinder charge. No change in nitrous oxide emissions is present in different sizes of particle distributions.

The relationship between noise level and load is shown in Fig. 4.22 for both operating modes. The noise level in the environment due to working of engine in twin fuel mode is always less as compared to pure diesel mode. The trend shows that it was always increasing as the load is increased in both the case of working. The noise level of engine is related with the combustion pressure and combustion process taking place in combustion chamber. The maximum value of noise in diesel mode is 90.8 decibel whereas in case of twin fuel mode the value was reduced to 86.7 decibel, which is about 4.5% less as compared to pure diesel mode working of engine.

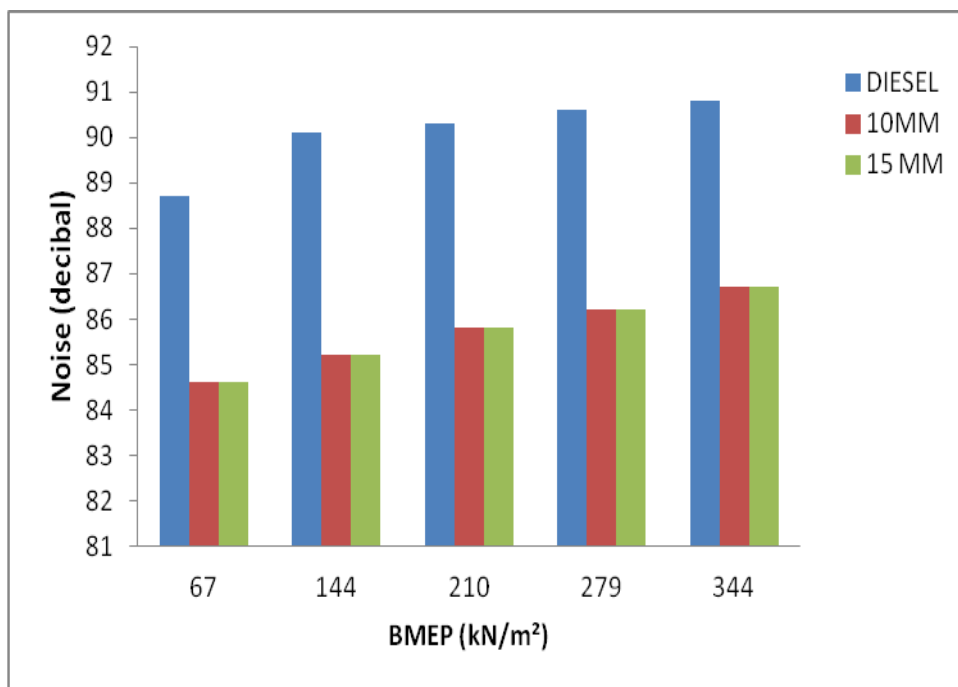


Fig.4.22: Noise level at different BMEP

The reason for less noise is due to the slow combustion rate of producer gas –diesel mixture as mentioned in mean gas temperature graph and lower peak pressure achieved in twin fuel mode of combustion. In case of diesel combustion the rate of combustion is very fast or we can say spontaneous but the combustion rate in twin fuel mode is slow due to slow burning nature of producer gas which results in reduced peak pressure. No change in noise level produced is present in different sizes of particle distributions.

4.6 ECONOMIC VIABILITY

The present work was carried out on biomass power generation system of 10 kW WBG (Ankur Make downdraft gasifier) installed capacity at Mechanical Engineering Department, Thapar University, Patiala, Punjab, India. The installation and the maintenance cost of the system for the turnkey operation were collected through the vendor. In present work, the cost of power generation and operation cost has been calculated. The cost of power production is calculated in view of the favourable performance of the gasifier system. The economic viability of the power production from gasifier arrangement was calculated by discounted cash flow method. The life cycle cost of energy production has been evaluated by considering the current economic condition. The characteristics like net present value, profitability index, internal rate of return and payback duration of the arrangement was calculated by considering the existing nature of discount rate in the market. The discounted cash flow technique was used to measure the economic feasibility of power generation system. This method measures the efficiency of the money invested and for which the flows of costs and profits over life period. These costs can be brought to refer to the particular point of time *i.e.*, present period by discounting them. For the success and commercialization of any new project, it is essential to know whether the project is economically viable or not. Economic analysis of the system was carried out by employing following indicators as,

- Net present worth
- Internal rate of return
- Profitability Index
- Payback duration
- Discounted payback period

Following parameters were considered to carry out economic analysis of gasifier system:

- Capital cost of the system @ INR 600000.
- Life of the system was considered as 15 years.
- Repair and maintenance cost at 18 per cent of initial investment spread over 15 years.
- Discount rate of the system was assumed 10 percent.
- Depreciation cost @ 3% of capital investment
- The labour cost was taken @ INR 200 per day.
- Biomass cost was INR 75 per day.
- Diesel cost was INR 50 per litre
- The annual operating days of gasifier system was 300 days.
- Power generation of 12 hour per day

- Sale price of electricity was INR 5 per kWh.

4.6.1 Net Present Value:

In this method, generally the discounted rate, which reflects the price of the investment funds, is used to arrive at costs and returns to a common point of time. These costs are subtracted from the return to get the net present values of the systems. The positive net present values indicate that the investment is worthwhile and the size of the net present value (NPV) indicates how worthwhile the project is in utilizing the resources to maximize income. Following expression was used to work out the net present value.

$$NPV = \sum_{t=1}^N \frac{R_t - C_t}{(1 + i)^t}$$

where, R is the returns in the year t, C is the costs in year t, N is the project life, i is the discount rate in per cent.

The decision criteria are:

If $NPV > 0$ Investment is worthwhile

$NPV < 0$ Investment is not worthwhile

$NPV = 0$ Neutral case.

The NPV of the system comes out to be **INR 769094.31** which is more than 1. So the present system is feasibly worthwhile without any government subsidy.

4.6.2 Internal Rate of Return:

The internal rate of return is a rate of return used in capital budgeting to measure and compare the profitability of investment. It is also called the discount rate that is required to bring the net present value (NPV) to zero. That is, the interest rate that would result in the present value of the capital investment, or cash outflow, being equal to the value of the total returns over time, or cash inflow. The IRR of a project is used as a benchmark; if the IRR of a specific project is higher than a company's required rate of return then the firm accepts the project. If, however, the IRR of a project is calculated to be below a company's required rate of return, the company does not move forward with the project. The internal rate of return, in this case, comes out to be of **29.37%** which is very significant for any type of investment.

4.6.3 Profitability Index:

The profitability index or benefit cost ratio measures the returns or benefit per unit of cost of investment.

$$PI \text{ or } BCR = \frac{\sum_{i=1}^N \frac{R_t}{(1+i)^t}}{\sum_{i=1}^N \frac{C_t}{(1+i)^t}}$$

The decision criteria are:

- If $PI > 1$ Investment is worthwhile
 $PI < 1$ Investment is not worthwhile
 $PI = 1$ Neutral case.

The PI or BCR value comes out to be **2.28** for the system and gives the system investment as worthwhile and justified.

4.6.4 Payback Duration:

This is the simplest of the techniques for evaluating an investment proposal. It is defined as the time period within which the initial investment of the project is recovered in the form of benefits. In other words, this is the length of time between the starting time of the project and the time when the initial investment is revert in the form of yearly benefits. Expressing it in notation

$$P = \frac{I}{C}$$

where, P is the payback period, I is the initial investment and C is the yearly net cash flow.

Payback period discriminates whether the project is feasible or not for the threshold lifetime. The net cash flow was calculated by deducting yearly operating costs from the gross annual income of the gasifier system. The cumulative net cash flow was then calculated for different years. For the system operating 12 h per day, the payback period was worked out to be **1215 days (3.33 years)**.

4.6.5 Discounted Payback Period:

It is used to calculate the length of time to recoup an investment based on the investment's discounted cash flows. By discounting each individual cash flow, the discounted payback period formula takes into consideration the time value of money.

$$DPP = \frac{\ln\left(\frac{1}{1 - \frac{O_1 * r}{CF}}\right)}{\ln(1 + r)}$$

where, O_1 is initial capital investment, r is rate of interest(0.10) and CF is periodic cash flow.

The discounted payback period formula is used in capital budgeting to compare a project or projects against the cost of the investment. The simple payback period formula can be used as a

quick measurement; however discounting each cash flow can provide a more accurate picture of the investment. As a simple way to explain, an initial cost of this project is INR 600000 and each cash flow is INR 180000 per year. The simple payback period formula would be 3.33 years, the initial investment divided by the cash flow each period. However, the discounted payback period would look at each of those INR 180000 cash flows based on its present value. The rate of interest is 10%, the present value of the first cash flow would be INR 163636.63, which is INR 180000 divided $1+r$. Each individual cash flow would then be discounted to its present value until it is determined how long it would take to recoup the original INR 600000. For the system operating 12 h per day, the discounted payback period was worked out to be **1553 days (4.254 years)**.

4.6.6 Operational Cost:

It is the ratio of total operation and maintenance cost with the total operating hours in a year.

$$\text{Cost of Operation} = \frac{O \& M \text{ Cost}}{Y * h}$$

where, O and M is operation and maintenance, Y is Number of operating days in a year and h is the number of operating hours in a day.

The total O and M cost is the sum of operation cost and maintenance cost which is equal to **INR 516500**. It includes the labour cost and cost of diesel (0.17 kg/kWh diesel consumption) and biomass to run the system.

The cost of operation comes out to be of INR **138.47** per hour in dual fuel mode and **INR 227.22** per hour for using diesel only mode.

4.6.7 Cost of Electricity generation (per kWh):

It is the ratio of total cost associated with depreciation and operation and maintenance of the system with the total operating hours in a year for running 10kW system.

$$\text{Cost of Electricity generation} = \frac{O \& M \text{ Cost} + \text{Depreciation cost of system}}{Y * h * 10}$$

Cost of electricity generation comes out to be for dual fuel mode running using 0.17 kg/kWh diesel consumption is **INR 14.34** per kWh whereas using diesel only(0.36 kg/kWh diesel consumption) the cost of electricity generation is 23 INR per kWh.

In totality the reduction of 40% in cost of operation and 38% reduction in cost of electricity generation will be possible using this dual fuel system.

In addition to this there is about 63332 kg of less carbon dioxide generation through dual fuel mode as the dual fuel mode power generation using biomass as gasifier fuel will reduce the

overall emissions of 80 % in carbon dioxide gas which will help in mitigation of CO₂ emissions by a higher value for Clean Development Mechanism. In terms of carbon credit, the system will generate at least 63 credits per year using this cotton stalk gasifier diesel engine setup.

4.7 UNCERTAINTY ANALYSIS

All the experimental measurements involve uncertainty in spite of all care and precaution to eliminate all possible sources of error from the measurements. Error and uncertainties in the experiments can arise from instrument selection, condition, calibration, environment, observation, reading and test planning. This error may be due to geometrical in-accuracy of the test apparatus and accuracy of measuring instruments. Uncertainty analysis is needed to prove the accuracy of the experimental results.

The uncertainty was estimated for experimental measurements (Klein and McClintock 1953 and Holman, 1994). The procedure of the uncertainty estimation is given below:

Let F is a parameter calculated using certain measured value as,

$$F = F(x_1, x_2, x_3, \dots, x_n) \tag{1}$$

Then uncertainty in measurement of F is given as follows:

$$\delta F = \left[\left(\frac{\partial F}{\partial x_1} \delta x_1 \right)^2 + \left(\frac{\partial F}{\partial x_2} \delta x_2 \right)^2 + \left(\frac{\partial F}{\partial x_3} \delta x_3 \right)^2 + \dots + \left(\frac{\partial F}{\partial x_n} \delta x_n \right)^2 \right]^{0.5} \tag{2}$$

Where, $\delta x_1, \delta x_2, \delta x_3, \dots, \delta x_n$ are the errors in measurements of parameter $x_1, x_2, x_3 \dots x_n$, δF is absolute uncertainty ;

Uncertainty in BTE =

$$\sqrt{(\text{uncertainty in dynamometer load})^2 + (\text{uncertainty in speed})^2 + (\text{uncertainty in fuel consumption})^2} \tag{3}$$

Uncertainty in BSEC =

$$\sqrt{(\text{uncertainty in crank angle encoder})^2 + (\text{uncertainty in speed})^2 + (\text{uncertainty in fuel consumption})^2} \tag{4}$$

The uncertainty values obtained in this experiment are calculated and listed as in Table 4.17.

Table 4.17: Uncertainty Measurements

Parameters	Uncertainty %
Brake Thermal Efficiency	2.24
Brake Specific Fuel Consumption	2.26
NO _x	1.06
CO	1.01
Smoke Density	0.34
Noise	0.55
Overall Uncertainty in Experimental	3.56

Uncertainty involved in the measurement of various parameters like speed, time period, temperature, fuel flow rate, torque by tachometer, stop watch, manometer, temperature sensor, burette, dynamometer etc. In view of the fact that absolute accuracy can never be achieved in any experimentation, it is essential to estimate accuracy achieved in the present experiments. The measurements accuracy is the function of resolution of the instruments. The uncertainty of brake thermal efficiency depends upon fuel flow rate, speed and load applied through dynamometer whereas brake specific fuel consumption depends upon fuel flow rate, speed and crank angle encoder. The uncertainty of the individual measurements has been taken from the manufacturer's data sheet. Since the equipment is within the calibration validity period, it is expected that the uncertainties of individual measurements are in accordance with the manufacturer's claim.

CHAPTER 5

CONCLUSION AND FUTURE SCOPE OF WORK

The overall studies based on the production of producer gas, fuel characterization, engine performance and exhaust emission and economical feasibility of using cotton stalk biomass in gasifier for dual fuel engine were carried out. Important findings on the engine performance and environmental aspects of electric power generation in dual fuel mode of operation while using cotton stalks in the gasifier are highlighted in the present study. This study proved that the diesel engine is capable of successful running in dual fuel mode of operation with the suitable biomass in the gasifier. The following conclusions can be drawn:

- i. The brake thermal efficiency of the dual fuel engine improved by 40% as compared to diesel due to higher amount of methane content in the producer gas.
- ii. The diesel consumption reduced to 50% in dual fuel when producer gas from cotton stalks is used with diesel in comparison to diesel only.
- iii. Carbon monoxide emission from the dual fuel mode of operation is higher than that when diesel alone is used under all load conditions.
- iv. Nitrous oxide level is 20% lower in the dual mode as compared to diesel fuel mode of running.
- v. The smoke emission from the dual fuel mode of operation is 22% lower than that when diesel alone is used under all load conditions and also reduction in noise level of 4.5% was observed in dual fuel mode.
- vi. The economic analysis of the system shows the fruitful result for the investment made on this system. The internal rate of return was 29.37% which was significant for investing in a project.
- vii. Also the cost of operation was 138.47 INR per hour for dual fuel engine whereas for diesel it comes out to be 230.00 INR per hour. And the cost of electricity generation in dual fuel mode is 14.34 INR per kWh.
- viii. With reduction of 60% GHG emissions, the gasifier operated dual fuel diesel engine is economically feasible option for power generation.

The waste/low-cost biomass feedstocks are used for producer gas generation. Hence, the power generation cost while using biomass is much cheaper than the conventional power generation cost. In addition to that mitigation of CO₂ emissions are also achieved by a higher value for Clean Development Mechanism. The agricultural biomass materials like

cotton stalks are suitable with little or no modification in the gasifier. The captive power generation plant can be installed depending on the availability of local biomass.

FUTURE SCOPE

Research Basis:

- Performance of cotton stalks in fluidized bed gasifier and the effect of particle size lower than 5mm of the cotton stalk in producer gas production into it.
- Mathematical modelling of the effect of the composition of various biomasses on producer gas composition.
- Long-term performance and endurance test evaluate the durability of the engine with prolonged operation on producer gas-diesel blends.
- Performance and emission tests can be carried out on multi-cylinder generator engines. Emission studies for measurement of particulate matter, and regulated emissions, as well as unregulated emissions such as polyaromatic hydrocarbons, volatile organic compounds, aldehydes etc., has to be carried out to reveal a total picture of environmental impact using producer gas-diesel fuel.
- A detailed long-term endurance test can be carried out to study the physical condition of various surfaces reflecting the extent of wear and carbon depositions due to the difference in performance of the different producer gas-diesel ratios and to conduct through tribological investigations.

Policy Matter:

- Legal framework should be there to enforce regulations on producer gas-diesel fuel use.
- Energy education on biomass utilization and storing information and database for wider information dissemination among the public at large should be taken up at a larger scale.
- Encouragement of community-based organizations like NGO's to act as clean and green energy service companies. These companies will be liable for operation and maintenance of gasifier and its allied system. Direct purchase of biomass from individual villagers will provide them earning the opportunity for living as well as waste disposal in a sustainable manner. Subsidy on the capital cost of gasifier will provide an extra boost. Additional soft loans of working capital for running the gasifier are also required.
- Regular information cum awareness programs should be conducted to convince the rural population about the potential of gasifier-based power generation and agricultural waste disposal method.

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APPENDIX

Table A1: Combustion parameters w.r.t crank angle

Crank angle	Diesel			Diesel gas		
	Cylinder pressure (bar)	Heat Release Rate (J/deg)	Mean Gas Temperature	Cylinder pressure (bar)	Heat Release Rate (J/deg)	Mean Gas Temperature
-360	0.53	0.01	8.52	0.19	-0.01	4.52
-359	0.53	0.04	8.58	0.19	-0.01	4.55
-358	0.53	0.06	8.66	0.19	0	4.59
-357	0.54	0.08	8.76	0.18	0.01	4.64
-356	0.54	0.1	8.89	0.18	0.01	4.69
-355	0.54	0.12	9.03	0.18	0.02	4.75
-354	0.54	0.14	9.2	0.18	0.02	4.82
-353	0.54	0.16	9.39	0.18	0.03	4.89
-352	0.53	0.18	9.6	0.17	0.04	4.97
-351	0.53	0.2	9.84	0.17	0.04	5.05
-350	0.53	0.22	10.1	0.17	0.05	5.14
-349	0.53	0.24	10.38	0.17	0.05	5.24
-348	0.53	0.26	10.69	0.16	0.06	5.35
-347	0.53	0.28	11.01	0.16	0.06	5.46
-346	0.53	0.3	11.36	0.16	0.06	5.58
-345	0.53	0.32	11.74	0.16	0.05	5.7
-344	0.52	0.34	12.13	0.15	0.05	5.83
-343	0.52	0.36	12.55	0.15	0.05	5.97
-342	0.52	0.38	12.99	0.15	0.06	6.11
-341	0.52	0.4	13.45	0.14	0.07	6.26
-340	0.52	0.42	13.94	0.14	0.09	6.42
-339	0.52	0.44	14.45	0.13	0.1	6.58
-338	0.52	0.46	14.98	0.13	0.1	6.74
-337	0.51	0.48	15.54	0.13	0.1	6.91
-336	0.51	0.5	16.12	0.13	0.1	7.08
-335	0.51	0.52	16.73	0.13	0.1	7.25
-334	0.51	0.54	17.35	0.13	0.1	7.43
-333	0.51	0.55	18	0.12	0.1	7.61
-332	0.51	0.57	18.67	0.12	0.11	7.8
-331	0.51	0.59	19.37	0.12	0.11	7.99
-330	0.51	0.61	20.08	0.12	0.11	8.2
-329	0.51	0.63	20.82	0.12	0.12	8.41
-328	0.51	0.65	21.58	0.12	0.12	8.64
-327	0.51	0.66	22.37	0.12	0.13	8.88
-326	0.51	0.68	23.17	0.11	0.13	9.14
-325	0.51	0.7	24	0.11	0.14	9.41

-324	0.51	0.71	24.85	0.11	0.14	9.69
-323	0.51	0.73	25.73	0.11	0.14	9.98
-322	0.51	0.74	26.61	0.11	0.15	10.28
-321	0.51	0.76	27.52	0.11	0.15	10.6
-320	0.51	0.77	28.44	0.11	0.15	10.92
-319	0.51	0.78	29.38	0.11	0.16	11.25
-318	0.51	0.8	30.33	0.11	0.16	11.59
-317	0.51	0.81	31.3	0.11	0.17	11.93
-316	0.51	0.82	32.28	0.11	0.17	12.27
-315	0.51	0.84	33.27	0.11	0.18	12.62
-314	0.51	0.85	34.28	0.11	0.18	12.97
-313	0.51	0.86	35.3	0.11	0.19	13.32
-312	0.51	0.87	36.33	0.11	0.19	13.67
-311	0.51	0.88	37.38	0.11	0.2	14.02
-310	0.51	0.89	38.44	0.11	0.2	14.38
-309	0.51	0.9	39.51	0.11	0.21	14.73
-308	0.51	0.91	40.6	0.11	0.21	15.1
-307	0.51	0.92	41.7	0.11	0.22	15.46
-306	0.51	0.93	42.81	0.11	0.23	15.84
-305	0.51	0.94	43.93	0.11	0.23	16.22
-304	0.51	0.95	45.07	0.11	0.24	16.6
-303	0.51	0.96	46.21	0.11	0.25	17
-302	0.51	0.97	47.37	0.11	0.25	17.39
-301	0.51	0.98	48.54	0.11	0.26	17.8
-300	0.51	0.99	49.72	0.11	0.26	18.21
-299	0.51	1	50.92	0.11	0.27	18.62
-298	0.51	1.01	52.12	0.11	0.27	19.04
-297	0.51	1.01	53.33	0.11	0.28	19.47
-296	0.51	1.02	54.55	0.12	0.28	19.89
-295	0.51	1.03	55.78	0.12	0.29	20.32
-294	0.51	1.03	57.02	0.12	0.29	20.76
-293	0.51	1.04	58.26	0.12	0.3	21.19
-292	0.51	1.05	59.52	0.12	0.3	21.63
-291	0.51	1.06	60.78	0.12	0.31	22.07
-290	0.51	1.06	62.06	0.12	0.31	22.51
-289	0.51	1.07	63.35	0.12	0.32	22.95
-288	0.51	1.08	64.65	0.12	0.33	23.4
-287	0.51	1.09	65.96	0.12	0.33	23.85
-286	0.51	1.1	67.29	0.12	0.34	24.31
-285	0.51	1.11	68.63	0.13	0.35	24.77
-284	0.51	1.12	69.99	0.13	0.35	25.24
-283	0.51	1.13	71.37	0.13	0.36	25.72
-282	0.52	1.14	72.77	0.13	0.37	26.21
-281	0.52	1.15	74.17	0.13	0.38	26.71

-280	0.52	1.16	75.6	0.13	0.38	27.21
-279	0.52	1.17	77.04	0.13	0.39	27.73
-278	0.52	1.18	78.49	0.13	0.4	28.26
-277	0.52	1.19	79.96	0.14	0.4	28.81
-276	0.52	1.19	81.44	0.14	0.41	29.36
-275	0.52	1.2	82.93	0.14	0.42	29.93
-274	0.53	1.21	84.44	0.14	0.42	30.51
-273	0.53	1.22	85.96	0.14	0.43	31.1
-272	0.53	1.22	87.49	0.14	0.43	31.71
-271	0.53	1.23	89.03	0.14	0.44	32.33
-270	0.53	1.24	90.58	0.15	0.44	32.96
-269	0.53	1.24	92.15	0.15	0.45	33.6
-268	0.54	1.25	93.72	0.15	0.45	34.26
-267	0.54	1.26	95.31	0.15	0.46	34.92
-266	0.54	1.26	96.91	0.15	0.46	35.6
-265	0.54	1.27	98.52	0.15	0.47	36.28
-264	0.54	1.28	100.14	0.16	0.47	36.97
-263	0.55	1.28	101.78	0.16	0.48	37.68
-262	0.55	1.29	103.42	0.16	0.48	38.39
-261	0.55	1.29	105.08	0.16	0.49	39.11
-260	0.55	1.3	106.75	0.16	0.49	39.84
-259	0.55	1.31	108.43	0.16	0.5	40.59
-258	0.56	1.31	110.12	0.17	0.5	41.34
-257	0.56	1.32	111.83	0.17	0.5	42.11
-256	0.56	1.33	113.55	0.17	0.51	42.9
-255	0.56	1.33	115.28	0.17	0.51	43.72
-254	0.57	1.34	117.03	0.17	0.51	44.53
-253	0.57	1.34	118.78	0.17	0.51	45.34
-252	0.57	1.34	120.54	0.18	0.51	46.14
-251	0.57	1.35	122.31	0.18	0.51	46.98
-250	0.58	1.35	124.09	0.18	0.51	47.89
-249	0.58	1.35	125.88	0.18	0.51	48.81
-248	0.58	1.36	127.68	0.18	0.51	49.73
-247	0.59	1.36	129.48	0.18	0.51	50.66
-246	0.59	1.37	131.29	0.19	0.51	51.6
-245	0.59	1.37	133.11	0.19	0.51	52.55
-244	0.6	1.37	134.94	0.19	0.51	53.51
-243	0.6	1.37	136.78	0.19	0.51	54.49
-242	0.6	1.38	138.63	0.19	0.5	55.48
-241	0.6	1.38	140.49	0.19	0.5	56.49
-240	0.61	1.38	142.35	0.19	0.5	57.51
-239	0.61	1.38	144.22	0.2	0.5	58.55
-238	0.61	1.38	146.09	0.2	0.49	59.6
-237	0.62	1.39	147.98	0.2	0.49	60.67

-236	0.62	1.39	149.87	0.2	0.49	61.75
-235	0.63	1.39	151.76	0.2	0.49	62.85
-234	0.63	1.39	153.66	0.2	0.49	63.96
-233	0.63	1.39	155.57	0.21	0.48	65.09
-232	0.64	1.39	157.48	0.21	0.48	66.24
-231	0.64	1.39	159.4	0.21	0.48	67.4
-230	0.64	1.39	161.32	0.21	0.48	68.58
-229	0.65	1.39	163.25	0.21	0.47	69.77
-228	0.65	1.38	165.17	0.21	0.47	70.98
-227	0.65	1.38	167.1	0.21	0.47	72.21
-226	0.66	1.38	169.03	0.22	0.46	73.45
-225	0.66	1.37	170.96	0.22	0.46	74.7
-224	0.67	1.37	172.88	0.22	0.46	75.96
-223	0.67	1.36	174.8	0.22	0.46	77.24
-222	0.67	1.36	176.73	0.22	0.45	78.53
-221	0.68	1.35	178.64	0.22	0.45	79.84
-220	0.68	1.34	180.56	0.22	0.45	81.15
-219	0.69	1.34	182.46	0.22	0.44	82.47
-218	0.69	1.33	184.36	0.23	0.43	83.8
-217	0.69	1.32	186.25	0.23	0.43	85.13
-216	0.7	1.31	188.12	0.23	0.42	86.47
-215	0.7	1.29	189.99	0.23	0.42	87.82
-214	0.71	1.28	191.84	0.23	0.41	89.17
-213	0.71	1.27	193.68	0.23	0.4	90.53
-212	0.72	1.25	195.5	0.23	0.4	91.89
-211	0.72	1.24	197.31	0.24	0.39	93.25
-210	0.72	1.23	199.09	0.24	0.39	94.62
-209	0.73	1.21	200.87	0.24	0.39	95.98
-208	0.73	1.2	202.62	0.24	0.38	97.35
-207	0.74	1.18	204.36	0.24	0.38	98.73
-206	0.74	1.17	206.09	0.24	0.38	100.1
-205	0.74	1.15	207.79	0.24	0.37	101.48
-204	0.75	1.14	209.48	0.24	0.37	102.85
-203	0.75	1.12	211.15	0.25	0.37	104.23
-202	0.76	1.1	212.8	0.25	0.37	105.6
-201	0.76	1.09	214.43	0.25	0.37	106.98
-200	0.76	1.07	216.03	0.25	0.37	108.35
-199	0.77	1.05	217.62	0.25	0.37	109.71
-198	0.77	1.03	219.19	0.25	0.38	111.07
-197	0.78	1.01	220.73	0.25	0.38	112.43
-196	0.78	0.99	222.24	0.26	0.39	113.77
-195	0.78	0.96	223.73	0.26	0.39	115.11
-194	0.79	0.94	225.19	0.26	0.39	116.43
-193	0.79	0.91	226.61	0.26	0.39	117.75

-192	0.8	0.88	228	0.26	0.39	119.04
-191	0.8	0.85	229.34	0.26	0.39	120.32
-190	0.8	0.82	230.64	0.27	0.4	121.59
-189	0.81	0.8	231.9	0.27	0.41	122.84
-188	0.81	0.78	233.14	0.27	0.42	124.08
-187	0.82	0.76	234.35	0.27	0.43	125.31
-186	0.82	0.74	235.54	0.27	0.45	126.54
-185	0.82	0.72	236.69	0.28	0.46	127.76
-184	0.83	0.73	237.83	0.28	0.48	128.99
-183	0.83	0.73	238.95	0.28	0.49	130.21
-182	0.83	0.7	240.13	0.28	0.51	131.45
-181	0.84	0.7	241.26	0.29	0.53	132.68
-180	0.84	0.69	242.38	0.29	0.55	133.93
-179	0.85	0.68	243.5	0.29	0.57	135.19
-178	0.85	0.67	244.62	0.3	0.59	136.46
-177	0.85	0.67	245.74	0.3	0.61	137.74
-176	0.86	0.66	246.86	0.3	0.62	139.04
-175	0.86	0.65	247.97	0.31	0.64	140.34
-174	0.87	0.64	249.08	0.31	0.66	141.66
-173	0.87	0.63	250.18	0.31	0.67	142.99
-172	0.88	0.61	251.27	0.32	0.68	144.33
-171	0.88	0.6	252.36	0.32	0.68	145.68
-170	0.88	0.58	253.43	0.33	0.7	147.03
-169	0.89	0.57	254.48	0.33	0.76	148.4
-168	0.89	0.56	255.53	0.34	0.82	149.78
-167	0.9	0.54	256.56	0.34	0.79	151.17
-166	0.9	0.53	257.59	0.35	0.7	152.59
-165	0.91	0.52	258.6	0.35	0.67	154.02
-164	0.91	0.51	259.61	0.36	0.72	155.47
-163	0.92	0.49	260.6	0.36	0.76	156.94
-162	0.93	0.48	261.58	0.37	0.76	158.43
-161	0.93	0.47	262.56	0.37	0.76	159.94
-160	0.94	0.46	263.53	0.38	0.75	161.47
-159	0.94	0.45	264.49	0.38	0.75	163.02
-158	0.95	0.44	265.45	0.39	0.77	164.59
-157	0.95	0.43	266.4	0.39	0.79	166.18
-156	0.96	0.42	267.34	0.4	0.81	167.79
-155	0.97	0.41	268.29	0.41	0.83	169.43
-154	0.97	0.4	269.24	0.41	0.84	171.1
-153	0.98	0.39	270.18	0.42	0.86	172.78
-152	0.98	0.37	271.11	0.43	0.88	174.49
-151	0.99	0.35	272.03	0.43	0.91	176.22
-150	1	0.33	272.93	0.44	0.93	177.95
-149	1	0.31	273.81	0.45	0.96	179.68

-148	1.01	0.29	274.67	0.45	0.98	181.42
-147	1.02	0.28	275.52	0.46	1.02	183.15
-146	1.03	0.26	276.35	0.47	1.05	184.87
-145	1.03	0.25	277.17	0.48	1.09	186.59
-144	1.04	0.23	277.98	0.49	1.12	188.3
-143	1.05	0.22	278.78	0.5	1.15	189.99
-142	1.06	0.21	279.57	0.51	1.18	191.66
-141	1.06	0.2	280.35	0.52	1.21	193.32
-140	1.07	0.2	281.14	0.53	1.24	194.97
-139	1.08	0.19	281.93	0.54	1.27	196.61
-138	1.09	0.19	282.73	0.55	1.29	198.23
-137	1.1	0.18	283.54	0.56	1.32	199.84
-136	1.11	0.17	284.35	0.58	1.34	201.43
-135	1.11	0.16	285.16	0.59	1.37	203
-134	1.12	0.16	285.97	0.6	1.4	204.54
-133	1.13	0.16	286.79	0.61	1.42	206.05
-132	1.14	0.16	287.62	0.63	1.45	207.53
-131	1.15	0.17	288.47	0.64	1.47	208.99
-130	1.16	0.17	289.34	0.66	1.49	210.42
-129	1.18	0.18	290.24	0.67	1.52	211.82
-128	1.19	0.2	291.16	0.69	1.53	213.21
-127	1.2	0.21	292.13	0.7	1.54	214.57
-126	1.21	0.21	293.13	0.72	1.53	215.92
-125	1.22	0.21	294.16	0.74	1.51	217.25
-124	1.24	0.19	295.21	0.75	1.49	218.53
-123	1.25	0.18	296.26	0.77	1.46	219.76
-122	1.26	0.17	297.31	0.79	1.43	220.95
-121	1.28	0.16	298.36	0.81	1.39	222.1
-120	1.29	0.15	299.41	0.83	1.35	223.21
-119	1.31	0.15	300.47	0.85	1.32	224.28
-118	1.32	0.14	301.54	0.87	1.29	225.33
-117	1.34	0.13	302.61	0.88	1.26	226.34
-116	1.35	0.12	303.68	0.9	1.22	227.35
-115	1.37	0.1	304.76	0.92	1.18	228.34
-114	1.39	0.09	305.84	0.94	1.14	229.32
-113	1.4	0.08	306.92	0.96	1.09	230.29
-112	1.42	0.06	308	0.98	1.05	231.27
-111	1.44	0.04	309.07	1	1	232.24
-110	1.46	0.03	310.15	1.03	0.97	233.23
-109	1.48	0.02	311.21	1.05	0.94	234.22
-108	1.5	0.02	312.29	1.07	0.91	235.23
-107	1.52	0.02	313.38	1.09	0.89	236.26
-106	1.54	0.03	314.49	1.11	0.88	237.33
-105	1.56	0.03	315.62	1.14	0.86	238.44

-104	1.59	0.04	316.79	1.16	0.85	239.6
-103	1.61	0.04	317.99	1.18	0.82	240.81
-102	1.63	0.05	319.23	1.21	0.79	242.09
-101	1.66	0.05	320.5	1.23	0.76	243.42
-100	1.68	0.04	321.8	1.26	0.73	244.8
-99	1.71	0.02	323.12	1.29	0.71	246.22
-98	1.74	0	324.44	1.31	0.7	247.71
-97	1.77	-0.02	325.75	1.34	0.69	249.25
-96	1.8	-0.03	327.06	1.37	0.68	250.85
-95	1.83	-0.04	328.38	1.4	0.68	252.51
-94	1.86	-0.06	329.7	1.43	0.66	254.24
-93	1.89	-0.08	331.03	1.46	0.64	256.03
-92	1.92	-0.12	332.35	1.49	0.61	257.88
-91	1.96	-0.17	333.66	1.53	0.56	259.76
-90	1.99	-0.23	334.92	1.56	0.5	261.67
-89	2.03	-0.3	336.13	1.59	0.44	263.57
-88	2.07	-0.38	337.27	1.63	0.38	265.46
-87	2.11	-0.46	338.31	1.67	0.31	267.34
-86	2.14	-0.54	339.26	1.7	0.25	269.2
-85	2.18	-0.61	340.12	1.74	0.19	271.04
-84	2.22	-0.67	340.88	1.78	0.15	272.87
-83	2.26	-0.72	341.57	1.82	0.11	274.7
-82	2.31	-0.75	342.2	1.86	0.1	276.53
-81	2.35	-0.76	342.8	1.9	0.09	278.39
-80	2.39	-0.76	343.4	1.95	0.09	280.28
-79	2.44	-0.76	344.02	1.99	0.1	282.22
-78	2.48	-0.76	344.67	2.04	0.1	284.21
-77	2.53	-0.76	345.35	2.09	0.12	286.25
-76	2.59	-0.76	346.07	2.14	0.14	288.33
-75	2.64	-0.75	346.81	2.19	0.18	290.46
-74	2.69	-0.73	347.59	2.24	0.22	292.64
-73	2.75	-0.69	348.43	2.3	0.27	294.89
-72	2.81	-0.64	349.36	2.36	0.33	297.22
-71	2.88	-0.58	350.39	2.43	0.39	299.62
-70	2.94	-0.52	351.53	2.49	0.46	302.09
-69	3.01	-0.47	352.8	2.57	0.52	304.63
-68	3.09	-0.41	354.2	2.64	0.57	307.25
-67	3.16	-0.38	355.73	2.72	0.61	309.93
-66	3.25	-0.38	357.36	2.8	0.64	312.66
-65	3.33	-0.41	359.06	2.89	0.66	315.42
-64	3.42	-0.47	360.76	2.98	0.69	318.19
-63	3.52	-0.52	362.43	3.08	0.7	320.95
-62	3.62	-0.56	364.06	3.18	0.7	323.69
-61	3.72	-0.56	365.65	3.29	0.68	326.42

-60	3.83	-0.55	367.27	3.4	0.65	329.14
-59	3.94	-0.53	368.93	3.52	0.62	331.84
-58	4.05	-0.51	370.66	3.65	0.58	334.51
-57	4.17	-0.49	372.47	3.77	0.54	337.14
-56	4.3	-0.48	374.35	3.91	0.48	339.75
-55	4.44	-0.49	376.3	4.05	0.44	342.33
-54	4.58	-0.54	378.29	4.2	0.42	344.92
-53	4.73	-0.61	380.29	4.35	0.42	347.52
-52	4.88	-0.7	382.24	4.51	0.43	350.17
-51	5.05	-0.78	384.11	4.68	0.41	352.88
-50	5.21	-0.83	385.91	4.86	0.35	355.67
-49	5.39	-0.85	387.65	5.04	0.24	358.52
-48	5.57	-0.86	389.39	5.24	0.11	361.41
-47	5.77	-0.87	391.16	5.44	-0.01	364.31
-46	5.97	-0.86	392.96	5.66	-0.12	367.24
-45	6.18	-0.84	394.82	5.88	-0.21	370.19
-44	6.41	-0.82	396.74	6.11	-0.28	373.21
-43	6.64	-0.79	398.75	6.35	-0.32	376.29
-42	6.89	-0.77	400.85	6.6	-0.3	379.47
-41	7.16	-0.75	403.03	6.87	-0.23	382.74
-40	7.44	-0.72	405.31	7.15	-0.14	386.13
-39	7.73	-0.66	407.67	7.45	-0.07	389.65
-38	8.04	-0.59	410.15	7.76	-0.04	393.26
-37	8.37	-0.5	412.78	8.1	-0.07	396.9
-36	8.73	-0.41	415.59	8.45	-0.12	400.48
-35	9.1	-0.31	418.59	8.83	-0.14	403.96
-34	9.5	-0.22	421.8	9.23	-0.14	407.34
-33	9.92	-0.15	425.21	9.65	-0.1	410.67
-32	10.37	-0.1	428.81	10.09	-0.04	414.01
-31	10.86	-0.07	432.56	10.56	0.05	417.47
-30	11.37	-0.05	436.44	11.06	0.17	421.13
-29	11.91	-0.02	440.43	11.59	0.31	425.09
-28	12.48	0.02	444.54	12.15	0.45	429.38
-27	13.08	0.07	448.77	12.75	0.53	434
-26	13.72	0.08	453.16	13.39	0.52	438.91
-25	14.4	0.06	457.68	14.08	0.43	443.99
-24	15.12	0	462.3	14.8	0.27	449.11
-23	15.87	-0.08	466.94	15.55	0.07	454.16
-22	16.66	-0.18	471.58	16.34	-0.15	459.04
-21	17.48	-0.29	476.18	17.16	-0.37	463.74
-20	18.34	-0.4	480.75	18.01	-0.55	468.24
-19	19.23	-0.48	485.26	18.88	-0.66	472.61
-18	20.15	-0.53	489.75	19.77	-0.69	476.9
-17	21.1	-0.56	494.24	20.69	-0.66	481.21

-16	22.07	-0.61	498.8	21.64	-0.62	485.61
-15	23.08	-0.71	503.41	22.61	-0.58	490.11
-14	24.1	-0.83	508.01	23.61	-0.56	494.73
-13	25.13	-0.89	512.53	24.63	-0.51	499.46
-12	26.17	-0.79	516.99	25.66	-0.4	504.29
-11	27.21	-0.49	521.52	26.7	-0.22	509.25
-10	28.23	-0.08	526.41	27.74	0.02	514.39
-9	29.26	0.28	531.87	28.77	0.24	519.78
-8	30.29	0.46	537.93	29.8	0.38	525.44
-7	31.31	0.47	544.36	30.8	0.4	531.31
-6	32.31	0.54	550.81	31.78	0.38	537.19
-5	33.24	0.87	557.12	32.69	0.46	542.95
-4	34.09	1.63	563.51	33.52	0.76	548.58
-3	34.86	3.28	570.49	34.25	1.31	554.25
-2	35.57	7.09	578.97	34.89	2.04	560.29
-1	36.28	14.34	591.22	35.44	2.83	566.94
0	37.1	24.77	612.03	35.92	3.61	574.33
1	38.35	34.88	647.5	36.34	4.43	582.44
2	40.38	39.88	701.14	36.68	5.41	591.31
3	43.38	37.25	768.41	36.94	6.72	601.13
4	47.02	30.53	838.06	37.12	8.69	612.3
5	50.57	24.23	897.55	37.26	11.88	625.48
6	53.27	19.98	944.71	37.39	16.71	641.93
7	54.99	17.88	980.5	37.62	22.84	663.97
8	55.83	16.69	1009.36	38.08	28.93	694.6
9	56.1	16.46	1033.33	38.91	33.15	735.99
10	55.94	16.57	1054.09	40.18	34.13	787.75
11	55.47	16.61	1073.25	41.75	32.25	845.75
12	54.81	16.7	1090.66	43.33	29.21	903.57
13	53.96	16.5	1106.68	44.61	26.41	955.36
14	52.98	16.33	1121.08	45.41	24.4	999.11
15	51.86	16.2	1133.5	45.71	22.96	1035.01
16	50.62	15.97	1144.43	45.61	22	1064.25
17	49.3	15.74	1153.69	45.21	21.41	1088.41
18	47.9	15.42	1161.45	44.58	20.91	1108.79
19	46.46	14.95	1167.73	43.8	20.49	1126.33
20	44.97	14.39	1172.44	42.91	20.09	1141.66
21	43.46	13.77	1175.45	41.94	19.63	1155.14
22	41.93	13.15	1176.76	40.91	19.17	1166.97
23	40.39	12.48	1176.42	39.83	18.6	1177.22
24	38.85	11.8	1174.58	38.73	17.89	1185.91
25	37.33	11.15	1171.22	37.6	17.12	1193.02
26	35.82	10.52	1166.52	36.45	16.24	1198.51
27	34.33	9.89	1160.62	35.29	15.28	1202.32

28	32.88	9.25	1153.64	34.12	14.26	1204.42
29	31.47	8.61	1145.65	32.95	13.25	1204.87
30	30.1	7.98	1136.72	31.77	12.33	1203.78
31	28.78	7.36	1126.92	30.6	11.54	1201.33
32	27.5	6.78	1116.33	29.44	10.87	1197.74
33	26.26	6.23	1105.04	28.29	10.26	1193.21
34	25.08	5.73	1093.17	27.18	9.66	1187.89
35	23.94	5.27	1080.82	26.1	9.08	1181.89
36	22.85	4.87	1068.1	25.06	8.53	1175.29
37	21.81	4.5	1055.15	24.06	8.03	1168.12
38	20.82	4.15	1042.05	23.09	7.59	1160.43
39	19.88	3.8	1028.87	22.17	7.19	1152.23
40	18.98	3.44	1015.63	21.28	6.81	1143.52
41	18.13	3.06	1002.33	20.43	6.46	1134.31
42	17.33	2.68	988.94	19.62	6.12	1124.68
43	16.56	2.28	975.42	18.85	5.79	1114.73
44	15.83	1.88	961.74	18.11	5.45	1104.56
45	15.13	1.49	947.89	17.41	5.09	1094.27
46	14.47	1.14	933.86	16.74	4.7	1083.87
47	13.83	0.83	919.71	16.1	4.32	1073.35
48	13.23	0.56	905.49	15.49	3.94	1062.73
49	12.65	0.33	891.27	14.91	3.58	1052.07
50	12.1	0.13	877.12	14.35	3.24	1041.45
51	11.58	-0.06	863.09	13.81	2.95	1030.91
52	11.08	-0.24	849.2	13.3	2.69	1020.47
53	10.61	-0.41	835.47	12.81	2.49	1010.13
54	10.17	-0.58	821.9	12.34	2.32	999.91
55	9.74	-0.75	808.48	11.89	2.19	989.83
56	9.34	-0.91	795.21	11.47	2.07	979.87
57	8.95	-1.07	782.06	11.06	1.96	970
58	8.59	-1.22	769.03	10.68	1.86	960.18
59	8.24	-1.36	756.13	10.31	1.75	950.37
60	7.91	-1.48	743.37	9.96	1.63	940.56
61	7.59	-1.59	730.75	9.63	1.5	930.75
62	7.29	-1.68	718.28	9.31	1.35	920.92
63	7.01	-1.76	706	9.01	1.18	911.05
64	6.73	-1.83	693.91	8.72	1	901.15
65	6.47	-1.9	682.03	8.45	0.83	891.23
66	6.22	-1.96	670.34	8.18	0.66	881.31
67	5.99	-2.03	658.84	7.93	0.5	871.42
68	5.76	-2.09	647.52	7.68	0.36	861.56
69	5.55	-2.15	636.37	7.45	0.24	851.76
70	5.34	-2.21	625.39	7.22	0.13	842.02
71	5.15	-2.27	614.57	7.01	0.03	832.34

72	4.96	-2.3	603.91	6.8	-0.06	822.72
73	4.78	-2.33	593.41	6.6	-0.15	813.16
74	4.61	-2.34	583.1	6.41	-0.23	803.65
75	4.45	-2.33	573	6.22	-0.31	794.19
76	4.29	-2.32	563.11	6.05	-0.38	784.77
77	4.14	-2.31	553.45	5.88	-0.45	775.42
78	4	-2.29	544.03	5.72	-0.5	766.16
79	3.86	-2.27	534.83	5.56	-0.54	757.02
80	3.73	-2.25	525.85	5.41	-0.58	748.01
81	3.61	-2.23	517.09	5.26	-0.61	739.15
82	3.49	-2.21	508.55	5.13	-0.63	730.44
83	3.38	-2.19	500.23	4.99	-0.66	721.9
84	3.27	-2.17	492.1	4.87	-0.68	713.51
85	3.17	-2.15	484.16	4.74	-0.7	705.28
86	3.07	-2.13	476.41	4.63	-0.72	697.2
87	2.97	-2.11	468.84	4.51	-0.75	689.27
88	2.88	-2.1	461.44	4.4	-0.77	681.53
89	2.8	-2.09	454.2	4.3	-0.8	673.98
90	2.71	-2.08	447.11	4.2	-0.83	666.65
91	2.64	-2.08	440.17	4.1	-0.87	659.54
92	2.56	-2.08	433.35	4.01	-0.91	652.65
93	2.49	-2.07	426.65	3.92	-0.96	645.96
94	2.41	-2.07	420.06	3.83	-1.01	639.47
95	2.35	-2.07	413.59	3.75	-1.06	633.14
96	2.28	-2.06	407.22	3.66	-1.11	626.95
97	2.22	-2.06	400.96	3.59	-1.17	620.87
98	2.16	-2.04	394.81	3.51	-1.22	614.9
99	2.1	-2.03	388.77	3.43	-1.27	609.01
100	2.04	-2.01	382.84	3.36	-1.31	603.21
101	1.99	-1.99	377.03	3.29	-1.34	597.5
102	1.94	-1.96	371.35	3.22	-1.37	591.89
103	1.89	-1.93	365.78	3.16	-1.39	586.37
104	1.84	-1.9	360.34	3.09	-1.4	580.93
105	1.79	-1.87	355.02	3.03	-1.41	575.55
106	1.75	-1.83	349.84	2.97	-1.41	570.21
107	1.7	-1.79	344.79	2.91	-1.41	564.9
108	1.66	-1.75	339.87	2.86	-1.4	559.63
109	1.62	-1.7	335.09	2.8	-1.38	554.39
110	1.58	-1.65	330.45	2.75	-1.36	549.19
111	1.55	-1.6	325.95	2.7	-1.34	544.05
112	1.51	-1.56	321.59	2.65	-1.32	538.97
113	1.48	-1.51	317.37	2.6	-1.3	533.98
114	1.44	-1.47	313.28	2.56	-1.28	529.07
115	1.41	-1.43	309.32	2.52	-1.26	524.26

116	1.38	-1.39	305.47	2.47	-1.25	519.56
117	1.35	-1.35	301.74	2.43	-1.23	514.98
118	1.33	-1.31	298.14	2.39	-1.22	510.5
119	1.3	-1.27	294.64	2.35	-1.21	506.13
120	1.28	-1.24	291.27	2.32	-1.21	501.87
121	1.25	-1.21	287.99	2.28	-1.21	497.71
122	1.23	-1.18	284.8	2.25	-1.22	493.65
123	1.21	-1.17	281.7	2.21	-1.24	489.68
124	1.18	-1.15	278.67	2.18	-1.26	485.81
125	1.16	-1.15	275.71	2.15	-1.29	482.01
126	1.14	-1.15	272.79	2.12	-1.32	478.29
127	1.12	-1.15	269.91	2.09	-1.36	474.64
128	1.1	-1.15	267.05	2.06	-1.4	471.04
129	1.08	-1.13	264.23	2.03	-1.44	467.49
130	1.07	-1.11	261.46	2	-1.49	463.97
131	1.05	-1.09	258.74	1.97	-1.55	460.47
132	1.03	-1.07	256.09	1.94	-1.61	456.98
133	1.02	-1.05	253.5	1.92	-1.68	453.48
134	1	-1.03	250.98	1.89	-1.74	449.97
135	0.98	-1.01	248.52	1.86	-1.8	446.45
136	0.97	-0.99	246.12	1.84	-1.85	442.92
137	0.95	-0.97	243.77	1.81	-1.9	439.4
138	0.94	-0.95	241.48	1.78	-1.94	435.89
139	0.93	-0.93	239.25	1.76	-1.97	432.4
140	0.91	-0.91	237.08	1.73	-2	428.94
141	0.9	-0.9	234.96	1.71	-2.03	425.49
142	0.89	-0.89	232.89	1.68	-2.06	422.07
143	0.88	-0.88	230.86	1.66	-2.09	418.66
144	0.87	-0.87	228.87	1.64	-2.11	415.28
145	0.86	-0.86	226.91	1.61	-2.14	411.9
146	0.84	-0.86	224.98	1.59	-2.16	408.54
147	0.83	-0.85	223.08	1.57	-2.18	405.18
148	0.82	-0.84	221.21	1.54	-2.21	401.83
149	0.81	-0.84	219.37	1.52	-2.23	398.47
150	0.8	-0.83	217.56	1.5	-2.26	395.12
151	0.8	-0.83	215.77	1.48	-2.28	391.75
152	0.79	-0.83	214.01	1.46	-2.3	388.38
153	0.78	-0.84	212.26	1.44	-2.32	385
154	0.77	-0.85	210.52	1.42	-2.34	381.61
155	0.76	-0.86	208.78	1.4	-2.35	378.2
156	0.75	-0.87	207.04	1.38	-2.36	374.79
157	0.74	-0.89	205.29	1.36	-2.37	371.37
158	0.74	-0.9	203.53	1.34	-2.37	367.97
159	0.73	-0.91	201.77	1.32	-2.37	364.57

160	0.72	-0.91	200	1.3	-2.36	361.12
161	0.71	-0.92	198.24	1.28	-2.35	357.56
162	0.7	-0.93	196.47	1.26	-2.34	353.93
163	0.7	-0.93	194.71	1.24	-2.32	350.38
164	0.69	-0.94	192.94	1.23	-2.3	346.94
165	0.68	-0.94	191.18	1.21	-2.27	343.49
166	0.67	-0.95	189.42	1.19	-2.25	339.98
167	0.67	-0.95	187.67	1.17	-2.22	336.43
168	0.66	-0.96	185.92	1.16	-2.2	332.86
169	0.65	-0.96	184.17	1.14	-2.18	329.27
170	0.65	-0.96	182.43	1.13	-2.17	325.67
171	0.64	-0.97	180.69	1.11	-2.17	322.07
172	0.63	-0.98	178.95	1.1	-2.17	318.46
173	0.63	-0.99	177.22	1.08	-2.18	314.85
174	0.62	-1	175.48	1.07	-2.2	311.21
175	0.61	-1.02	173.73	1.06	-2.22	307.55
176	0.61	-1.04	171.97	1.04	-2.25	303.86
177	0.6	-1.07	170.17	1.03	-2.28	300.13
178	0.59	-1.09	168.35	1.01	-2.32	296.35
179	0.59	-1.13	166.49	1	-2.36	292.52
180	0.58	-1.16	164.59	0.99	-2.41	288.63
181	0.57	-1.2	162.65	0.97	-2.45	284.68
182	0.57	-1.23	160.65	0.96	-2.49	280.67
183	0.56	-1.27	158.61	0.95	-2.53	276.6
184	0.55	-1.3	156.51	0.93	-2.57	272.46
185	0.55	-1.33	154.36	0.92	-2.61	268.27
186	0.54	-1.37	152.17	0.9	-2.65	264.02
187	0.53	-1.4	149.92	0.89	-2.69	259.7
188	0.52	-1.44	147.62	0.87	-2.73	255.31
189	0.52	-1.47	145.28	0.86	-2.76	250.85
190	0.51	-1.5	142.88	0.84	-2.8	246.33
191	0.5	-1.53	140.44	0.83	-2.84	241.73
192	0.49	-1.57	137.95	0.81	-2.88	237.08
193	0.49	-1.6	135.41	0.8	-2.92	232.36
194	0.48	-1.64	132.82	0.78	-2.96	227.58
195	0.47	-1.68	130.18	0.77	-2.99	222.75
196	0.46	-1.71	127.48	0.75	-3.03	217.87
197	0.45	-1.75	124.72	0.74	-3.07	212.95
198	0.44	-1.79	121.92	0.72	-3.1	207.99
199	0.43	-1.82	119.05	0.7	-3.14	202.99
200	0.42	-1.86	116.13	0.69	-3.18	197.97
201	0.41	-1.9	113.15	0.67	-3.22	192.91
202	0.41	-1.94	110.11	0.65	-3.25	187.81
203	0.4	-1.97	107.02	0.64	-3.27	182.68

204	0.39	-1.99	103.87	0.62	-3.29	177.51
205	0.38	-2	100.68	0.6	-3.29	172.32
206	0.36	-2.01	97.47	0.59	-3.28	167.12
207	0.35	-2.02	94.23	0.57	-3.26	161.9
208	0.34	-2.01	90.99	0.55	-3.22	156.69
209	0.33	-1.99	87.76	0.53	-3.18	151.5
210	0.32	-1.97	84.55	0.52	-3.13	146.33
211	0.31	-1.94	81.38	0.5	-3.07	141.2
212	0.3	-1.91	78.25	0.48	-3.01	136.12
213	0.29	-1.88	75.16	0.47	-2.94	131.09
214	0.28	-1.84	72.13	0.45	-2.87	126.12
215	0.27	-1.79	69.17	0.43	-2.78	121.22
216	0.26	-1.73	66.28	0.42	-2.7	116.37
217	0.25	-1.66	63.48	0.4	-2.6	111.61
218	0.24	-1.6	60.79	0.39	-2.5	106.92
219	0.23	-1.53	58.2	0.37	-2.4	102.33
220	0.22	-1.45	55.73	0.36	-2.3	97.84
221	0.21	-1.38	53.38	0.35	-2.19	93.46
222	0.21	-1.3	51.14	0.33	-2.09	89.21
223	0.2	-1.22	49.03	0.32	-1.98	85.09
224	0.19	-1.14	47.06	0.31	-1.88	81.1
225	0.18	-1.06	45.21	0.3	-1.77	77.27
226	0.18	-0.97	43.5	0.29	-1.65	73.58
227	0.17	-0.89	41.92	0.28	-1.54	70.04
228	0.17	-0.8	40.49	0.27	-1.43	66.66
229	0.16	-0.71	39.19	0.26	-1.31	63.42
230	0.16	-0.62	38.04	0.26	-1.2	60.34
231	0.15	-0.54	37.04	0.25	-1.09	57.43
232	0.15	-0.45	36.17	0.24	-0.98	54.67
233	0.15	-0.37	35.45	0.24	-0.87	52.07
234	0.15	-0.29	34.87	0.23	-0.78	49.63
235	0.15	-0.2	34.42	0.23	-0.68	47.33
236	0.14	-0.13	34.11	0.22	-0.6	45.18
237	0.14	-0.05	33.93	0.22	-0.52	43.17
238	0.14	0.01	33.87	0.22	-0.45	41.3
239	0.15	0.08	33.93	0.22	-0.39	39.56
240	0.15	0.13	34.1	0.22	-0.33	37.94
241	0.15	0.17	34.36	0.22	-0.29	36.46
242	0.15	0.21	34.7	0.22	-0.25	35.09
243	0.15	0.24	35.11	0.22	-0.23	33.85
244	0.16	0.27	35.58	0.22	-0.2	32.73
245	0.16	0.29	36.1	0.22	-0.19	31.73
246	0.16	0.3	36.65	0.22	-0.17	30.85
247	0.17	0.32	37.24	0.22	-0.16	30.09

248	0.17	0.33	37.86	0.22	-0.16	29.45
249	0.18	0.34	38.5	0.22	-0.15	28.93
250	0.18	0.34	39.16	0.22	-0.15	28.52
251	0.19	0.35	39.84	0.23	-0.16	28.22
252	0.19	0.35	40.53	0.23	-0.16	28.02
253	0.2	0.36	41.23	0.23	-0.17	27.92
254	0.2	0.36	41.94	0.23	-0.17	27.9
255	0.21	0.36	42.66	0.23	-0.18	27.96
256	0.21	0.36	43.39	0.24	-0.19	28.09
257	0.22	0.36	44.12	0.24	-0.2	28.27
258	0.23	0.35	44.85	0.24	-0.2	28.5
259	0.23	0.34	45.58	0.24	-0.21	28.77
260	0.24	0.34	46.31	0.24	-0.22	29.07
261	0.25	0.33	47.03	0.25	-0.22	29.39
262	0.25	0.31	47.75	0.25	-0.23	29.72
263	0.26	0.29	48.44	0.25	-0.24	30.05
264	0.27	0.27	49.12	0.25	-0.25	30.38
265	0.27	0.25	49.77	0.25	-0.26	30.69
266	0.28	0.22	50.39	0.26	-0.27	30.98
267	0.29	0.19	50.98	0.26	-0.28	31.26
268	0.3	0.16	51.53	0.26	-0.29	31.52
269	0.3	0.13	52.04	0.26	-0.31	31.76
270	0.31	0.09	52.5	0.27	-0.32	31.97
271	0.32	0.06	52.91	0.27	-0.33	32.17
272	0.33	0.02	53.27	0.27	-0.34	32.34
273	0.33	-0.02	53.58	0.27	-0.35	32.49
274	0.34	-0.05	53.84	0.27	-0.36	32.62
275	0.35	-0.09	54.04	0.28	-0.37	32.73
276	0.35	-0.12	54.19	0.28	-0.38	32.82
277	0.36	-0.16	54.29	0.28	-0.39	32.87
278	0.37	-0.19	54.34	0.28	-0.4	32.9
279	0.37	-0.23	54.35	0.28	-0.41	32.9
280	0.38	-0.26	54.3	0.29	-0.43	32.87
281	0.39	-0.3	54.21	0.29	-0.44	32.81
282	0.39	-0.34	54.06	0.29	-0.45	32.71
283	0.4	-0.38	53.86	0.29	-0.47	32.58
284	0.4	-0.42	53.6	0.29	-0.49	32.42
285	0.41	-0.45	53.28	0.29	-0.5	32.22
286	0.41	-0.49	52.91	0.3	-0.52	31.98
287	0.42	-0.53	52.48	0.3	-0.53	31.71
288	0.42	-0.56	51.99	0.3	-0.55	31.4
289	0.43	-0.6	51.45	0.3	-0.57	31.04
290	0.43	-0.63	50.86	0.3	-0.58	30.65
291	0.44	-0.66	50.22	0.3	-0.6	30.22

292	0.44	-0.69	49.53	0.3	-0.62	29.76
293	0.44	-0.72	48.8	0.3	-0.63	29.26
294	0.45	-0.75	48.02	0.3	-0.65	28.73
295	0.45	-0.77	47.2	0.3	-0.66	28.18
296	0.45	-0.79	46.35	0.3	-0.67	27.6
297	0.45	-0.81	45.46	0.3	-0.68	27
298	0.45	-0.82	44.54	0.3	-0.68	26.39
299	0.46	-0.83	43.61	0.3	-0.68	25.75
300	0.46	-0.83	42.65	0.3	-0.68	25.11
301	0.46	-0.84	41.69	0.29	-0.68	24.46
302	0.46	-0.84	40.72	0.29	-0.68	23.79
303	0.46	-0.84	39.74	0.29	-0.67	23.13
304	0.46	-0.84	38.75	0.29	-0.66	22.46
305	0.46	-0.84	37.77	0.28	-0.65	21.79
306	0.46	-0.84	36.79	0.28	-0.64	21.12
307	0.46	-0.83	35.8	0.28	-0.63	20.46
308	0.46	-0.83	34.82	0.28	-0.62	19.8
309	0.46	-0.82	33.84	0.27	-0.61	19.14
310	0.46	-0.82	32.87	0.27	-0.61	18.49
311	0.46	-0.81	31.91	0.27	-0.59	17.85
312	0.46	-0.8	30.95	0.27	-0.58	17.21
313	0.46	-0.78	30.01	0.26	-0.57	16.58
314	0.46	-0.77	29.08	0.26	-0.56	15.96
315	0.46	-0.76	28.17	0.26	-0.54	15.35
316	0.46	-0.74	27.28	0.25	-0.53	14.75
317	0.46	-0.73	26.4	0.25	-0.51	14.16
318	0.46	-0.72	25.54	0.25	-0.49	13.59
319	0.46	-0.7	24.7	0.24	-0.48	13.03
320	0.46	-0.68	23.87	0.24	-0.46	12.5
321	0.46	-0.67	23.07	0.24	-0.44	11.99
322	0.46	-0.65	22.29	0.23	-0.42	11.49
323	0.46	-0.63	21.54	0.23	-0.41	11.03
324	0.46	-0.61	20.8	0.23	-0.39	10.58
325	0.46	-0.59	20.1	0.22	-0.37	10.16
326	0.46	-0.58	19.41	0.22	-0.35	9.75
327	0.46	-0.56	18.75	0.22	-0.33	9.37
328	0.46	-0.55	18.1	0.22	-0.32	9
329	0.46	-0.53	17.48	0.21	-0.3	8.65
330	0.46	-0.51	16.87	0.21	-0.29	8.32
331	0.46	-0.5	16.29	0.21	-0.28	8
332	0.46	-0.48	15.72	0.21	-0.26	7.7
333	0.46	-0.47	15.17	0.21	-0.25	7.41
334	0.46	-0.45	14.64	0.21	-0.24	7.13
335	0.47	-0.43	14.13	0.2	-0.23	6.87

336	0.47	-0.42	13.64	0.2	-0.22	6.61
337	0.47	-0.4	13.17	0.2	-0.21	6.36
338	0.47	-0.39	12.72	0.2	-0.2	6.12
339	0.47	-0.37	12.29	0.2	-0.19	5.89
340	0.47	-0.35	11.88	0.2	-0.18	5.68
341	0.48	-0.33	11.49	0.19	-0.17	5.47
342	0.48	-0.31	11.13	0.19	-0.16	5.29
343	0.48	-0.29	10.79	0.19	-0.14	5.12
344	0.48	-0.27	10.47	0.19	-0.13	4.97
345	0.48	-0.25	10.18	0.19	-0.12	4.83
346	0.49	-0.24	9.91	0.19	-0.11	4.72
347	0.49	-0.22	9.66	0.19	-0.1	4.62
348	0.49	-0.2	9.44	0.19	-0.09	4.54
349	0.5	-0.18	9.24	0.19	-0.08	4.47
350	0.5	-0.16	9.07	0.19	-0.07	4.42
351	0.5	-0.15	8.91	0.19	-0.06	4.38
352	0.51	-0.12	8.78	0.19	-0.05	4.35
353	0.51	-0.12	8.67	0.19	-0.05	4.34
354	0.51	-0.22	8.58	0.19	-0.09	4.33
355	0.52	-0.66	8.4	0.19	-0.24	4.29
356	0.51	-0.08	7.89	0.19	-0.03	4.05
357	0.49	-0.05	6.36	0.18	-0.02	3.29
358	0.4	-0.03	4.07	0.14	-0.01	2.11
359	0.26	0	0	0.09	0	0

Table A2: Engine performance parameters w.r.t. BMEP

BMEP (kN/m ²)	Specific fuel consumption(kg/kWh)			Brake thermal efficiency(%)			Brake specific energy consumption(MJ/kWh)		
	Diesel	10MM	15 MM	Diesel	10MM	15 MM	Diesel	10MM	15 MM
67	0.89	0.61	0.56	9.6	13.97	14.4	40.05	259.45	284.73
144	0.54	0.34	0.29	15.74	24.93	26.62	24.3	129.30	140.58
210	0.43	0.26	0.24	19.79	33.02	33.8	19.35	88.14	96.31
279	0.37	0.19	0.2	23.1	41.36	42.2	16.65	65.55	72.76
344	0.36	0.17	0.17	24.02	43.05	43.8	16.2	53.73	59.19

Table A3: Engine emissions w.r.t. BMEP

BMEP (kN/m ²)	Carbon monoxide emissions (% by vol.)			Nitrous oxide(ppm)			Smoke density (%)		
	Diesel	10MM	15 MM	Diesel	10MM	15 MM	Diesel	10MM	15 MM
67	26	464	470	10	5	5	2.7	1.9	1.9
144	21	229	233	13	6	6	2.8	2	1.9
210	15	114	121	11	5	5	2.9	2.2	2.1
279	9	69	70	10	5	5	3.2	2.5	2.4
344	6	47	47	6	5	5	3.5	2.7	2.7

Table A4: Engine noise w.r.t. BMEP

BMEP (kN/m ²)	Noise level(dB)		
	Diesel	10MM	15 MM
67	88.7	84.6	84.6
144	90.1	85.2	85.2
210	90.3	85.8	85.8
279	90.6	86.2	86.2
344	90.8	86.7	86.7

Table A5: List of instruments and their uncertainty

Instrument	Percentage Uncertainty
Speed measuring unit	0.1
Digital stop watch	0.5
Manometer	1
Temperature	1
Burette for fuel measurement	2
Eddy current dynamometer	1
Orifice meter	1
Crank angle encoder	0.3
Gas Analyzer	Accuracy
NO _x	± 0.1
CO	± 1
Smoke Density	± 0.01
Noise	± 0.5

Biomass-based gasifiers for internal combustion (IC) engines—A review

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Abstract. The world is facing severe problems of energy crisis and environmental problem. This situation makes people to focus their attention on sustainable energy resources for their survival. Biomass is recognized to be the major potential source for energy production. There are ranges of biomass utilization technologies that produce useful energy from biomass. Gasification is one of the important techniques out of direct combustion, anaerobic digestion – Biogas, ethanol production. Gasification enables conversion of these materials into combustible gas (producer gas), mechanical and electrical power, synthetic fuels, and chemical. The gasification of biomass into useful fuel enhances its potential as a renewable energy resource. This paper gives a comprehensive review of the techniques used for utilizing biomass, experimental investigation on biomass fuels, characterization, merits, demerits and challenges faced by biomass fuels.

Keywords. Biomass; gasification; producer gas.

1. Introduction

A large population in the world are still not being serviced with energy needs at the minimum level even in the 21st century. This is true with the developing nations like India, Bangladesh, Sri Lanka, Pakistan, Latin American countries like Chile, Costa Rica, Brazil, etc., African countries like Zambia, Uganda, Zimbabwe, etc. and many others. Most of these countries are characterized by a large part of the population in scattered locales – in villages and hamlets. These remote locations make it uneconomical to extend the centralized grid. In addition, their economic structure is not strong towards importing oil for power generation applications. Further, the environmental considerations to reduce GHG have forced conservation of the use of fossil fuel. This has become one of the factors for the nations to reduce the use of fossil fuel and adopt suitable renewable energy device. In the renewable energy scenario dominated by solar, wind and micro/mini hydel, biomass is beginning to look promising in the view of new emerging technologies. Even though each of the above energy sources has a niche market, biomass has been playing a key role

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in the renewable energy sector. The modern bio-energy has received comparatively little fiscal and financial incentive unlike its counterpart, namely the solar photovoltaics. However, for reasons like the cost effectiveness and availability factor, biomass-based technologies are becoming popular as they have edge over other renewable. India is an oil-importing country, with nearly 70% of its population living in half million villages and hamlets across the country and rich in bio-resources is ideally suited for biomass-based technologies. The term biomass is used for all organic materials which are combustible in nature, mainly plant and animal origin present in land and aquatic environments. Biomass includes by-product and residue of crop farming and processing industries such as straw, husk, cobs, stalks, leaves, bark, fruits, cutting vines, etc., in addition to animal refuses and plant products used in agro-industrial processing such as grains, bean, flower and some special products such as cassava, seaweeds, etc. (Klass 1998; McKendry 2002; Rathore *et al* 2009).

With respect to global issues of sustainable energy and reduction in emission of greenhouse gases, biomass is getting increased attention as a potential for power generation. Biomass is not yet competitive with fossil fuels. Fossil fuel contributes to the major part of world's total energy consumption. According to the World Energy Assessment report, 80% of the world's primary energy consumption is contributed by fossil fuel, 14% by renewable (out of which biomass contributes 9.5%) and 6% by nuclear energy sources (McKendry 2002; Rathore *et al* 2009).

The process of gasification to produce combustible from organic feeds was used in blast furnaces over 180 years ago. The possibility of using this gas for heating and power generation was soon realized and there emerged in Europe producer gas systems, which used charcoal and peat as feed material. At the turn of the century, petroleum gained wider use as a fuel, but during both world wars and particularly World War II, shortage in petroleum supplies led to widespread re-introduction of gasification. By 1945 the gas was being used to power trucks, buses and agricultural and industrial machines. It is estimated that there were close to 9000,000 vehicles running on producer gas all over the world.

After World War II, the lack of strategic impetus and the availability of cheap fossil fuels led to general decline in the producer gas industry. Biomass gasifiers are being developed around the world today to produce CO₂ neutral energy. Gasification is a thermo chemical process where biomass is converted into a combustible producer gas. The main components in producer gas are N₂; H₂; CO; CO₂ and CH₄, and it is often used as fuel in an internal combustion (IC) engine (Bridgewater 2003). Gasification of woody biomass has been a well-known technology for more than five decades. Section 2 deals with biomass utilization, section 3 contains details on gasifiers. Sections 4 and 5 present review of past experiments and conclusion, respectively.

2. Biomass utilization techniques

There are wide ranges of biomass utilization technologies that produce useful energy from biomass. The commonly used techniques for utilizing biomass are elaborated below.

2.1 Direct combustion

Combustion, which is used in many applications, is the most direct process for converting biomass into usable energy. Since pre-historical inhabitants of this planet learnt how to make fire, they converted biomass to useful energy by burning wood in a fireplace or woodstove. Ever since the earliest inhabitants of this planet burned wood in their fireplaces, direct biomass burning has been a source of energy for meeting human needs until the present time. Direct combustion is

a thermo chemical conversion process utilizing the major feedstock such as wood, agricultural waste, municipal solid waste.

The energy produced by direct combustion process is heat and steam. Despite its apparent simplicity, direct combustion is a complex process from a technological point of view. High reaction rates and high heat release and many reactants and reaction schemes are involved. In order to analyse the combustion process, a division is made between the place where the biomass fuel is burned (the furnace) and the place where the heat from the flue gas is exchanged for a process medium or energy carrier (the heat exchanger).

Properly designed industrial biomass combustion facilities can burn all types of above listed biomass fuel. In combustion process, volatile hydrocarbons (C_xH_y) are formed and burned in a hot combustion zone. Combustion technologies convert biomass fuels into several forms of useful energy for commercial and/or industrial uses. In a furnace, the biomass fuel converted via combustion process into heat energy. The heat energy is released in the form of hot gases to heat exchanger that switches thermal energy from the hot gases to the process medium (steam, hot water or hot air).

Direct combustion systems are of either fixed bed or fluidized-bed systems. Fixed-bed systems are basically distinguished by types of grates and the way the biomass fuel is supplied to or transported through the furnace. In stationary or travelling grate combustor, a manual or automatic feeder distributes the fuel onto a grate, where the fuel burns. Combustion air enters from below the grate. In the stationary grate design, ashes fall into a pit for collection. In contrast, a travelling grate system has a moving grate that drops the ash into a hopper.

Fluidized-bed combustors (FBC) burn biomass fuel in a hot bed of granular, non-combustible material, such as sand, limestone, or other. Injection of air into the bed creates turbulence resembling a boiling liquid. The turbulence distributes and suspends the fuel. This design increases heat transfer and allows for operating temperatures below 970°C , reducing NO_x emissions. Depending on the air velocity, a bubbling fluidized bed or circulating fluidized bed is created. The most important advantages (comparing to fixed bed systems) of fluidized-bed combustion system are:

- Flexibility to changes in biomass fuel properties, sizes and shapes
- Acceptance of biomass fuel moisture content up to 60%
- Can handle high-ash fuels and agricultural biomass residue (>50%)
- Compact construction with high heat exchange and reaction rates
- Low NO_x emissions
- Low excess air factor, below 1.2 to 1.4, resulting in low heat losses from flue gas.

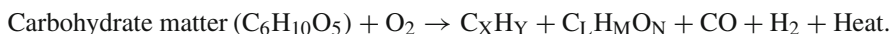
Two cycles are possible for combining electric power generation with process steam production. Steam can be used in process first and then re-routed through a steam turbine to generate electric power. This arrangement is called a bottoming cycle. In the alternate cycle, steam from the boiler passes first through a steam turbine to produce electric power. The back-pressure (or extracted) steam from the steam turbine is then used for processes or for heating (or cooling) purposes. This arrangement is called a topping cycle, which is the more common cycle.

2.2 Biomass gasification

Gasification, production of combustible gas from carbon containing materials, is already an old technology. The first record of its commercial application originates from so called dry distillation (or pyrolysis – heating of feedstock in the absence of O_2 , resulting in thermal decomposition

of fuel into volatile gases and solid carbon) dates back to 1812 (Gas Company in London). The first attempt to use producer gas to fire the internal combustion engine was carried out in 1881. Biomass gasification was reintroduced during the World War II as the consequence of unavailability of petroleum. After the end of the war gasifier systems were substituted with engines driven by liquid fossil fuels again. It was not before the 1970s energy crisis when gasification came back for the third time through its history. Biomass gasification is other thermo chemical conversion process utilizing the following major feedstock: wood, agricultural waste, municipal solid waste.

Chemical process of gasification means the thermal decomposition of hydrocarbons from biomass in a reducing (oxygen-deficient) atmosphere. The process usually takes place at about 850°C. Because the injected air prevents the ash from melting, steam injection is not always required. A biomass gasifier can operate under atmospheric pressure or elevated pressure. The resulting gas product, the synthetic gas, contains combustible gases – hydrogen (H₂) and carbon monoxide (CO) as the main constituents; by-products are liquids and tars, charcoal and mineral matter (ash or slag). In general, the gasifying agent can be air, oxygen (O₂) or oxygen-enriched air. For biomass gasification, air is normally used as oxidant (oxygen as the oxidant agent is preferred in high capacity fossil fuel gasification systems). The net product of air gasification can be found by summing up the partial reactions, as follows:



The biggest advantage of gasification is the variety of feed stocks as well as products. The produced synthetic gas can be utilized not only as the fuel for power generation but also as the feedstock for chemical industry.

2.3 Anaerobic digestion – Biogas

As per records, Alessandro Volta first discovered biogas in 1776 and Humphrey Davy was the first to pronounce the presence of combustible gas methane in the farmyard manure in as early as 1800. Anaerobic digestion is a biological process that produces a gas principally composed of methane (CH₄) and carbon dioxide (CO₂), known as biogas. The biogas is produced from the following major organic wastes:

- Solid and liquid animal manure
- Agricultural plant waste
- Waste from agricultural products processing industry
- Organic components in town waste
- Waste waters
- Landfills.

Anaerobic digestion can be used to produce valuable energy from waste streams of natural materials or to lower the pollution potential of a waste stream. Biogas plant has a self-consumption of energy to keep the sludge warm. This is typically 20% of the energy production for a well-designed biogas plant. Anaerobic digestion is a complex biochemical reaction carried out in a number of steps by several types of microorganisms that require little or no oxygen to live. During the process of biogas, principally approximately 65% methane (CH₄) and about 30% carbon dioxide (CO₂), is produced. The amount of biogas produced varies with the amount of organic waste fed to the digester and temperature influences the rate of decomposition. Several

different types of bacteria work in stages together, to break down complex organic wastes, resulting in the production of biogas. Controlled anaerobic digestion requires an airtight chamber, called a digester. A mixture of CH₄ with CO₂ is making up more than 90% of the total biogas composition. The remaining gases are usually smaller amounts of H₂S, N₂, H₂, methylmercaptans and O₂.

2.4 Ethanol production

Starch content of biomass feed stocks like corn, potatoes, beets, sugarcane, wheat, barley, and similar can be converted by fermentation process into alcohol (ethanol). Fermentation is the biochemical process that converts sugars into ethanol (alcohol). In contrast to biogas production, fermentation takes place in the presence of air and is, therefore, a process of aerobic digestion.

Ethanol producers use specific types of enzymes to convert starch crops such as corn, wheat and barley to fermentable sugars. Some crops, such as sugar cane and sugar beets, naturally contain fermentable sugars. Hydrolysis is the technology, which converts cellulose to alcohols through fermentation. Ethyl alcohol can be produced from a Variety of sugars by fermentation with years. Molasses is diluted with water to a sugar content of about 20% by weigh acidified to pH 4.5 and then mixed with yeast culture in a fermentor. Ammonia is used to reduce acidity. When 8–10 percent alcohol is accumulated, then liquid is distilled, fractionated and rectified 2.5 litres of cane molasses produces about one litre of alcohol.

Ethanol is easier to transport and store than hydrogen, fuel reforming (using a chemical process to extract hydrogen from fuel) may be a practical way to provide hydrogen to fuel cells in vehicles or for remote stationary applications. Latin America, dominated by Brazil, is the world's largest production region of bio-ethanol. As the value of bio-ethanol is increasingly being recognized, more and more policies to support development and implementation of ethanol as a fuel are being introduced.

Among all the alternatives of technology used, gasification is the best suitable alternative in view of the following points (Khan 2009):

- Gasification offers high flexibility in terms of various biomass materials as feedstock.
- Gasification has thermo-chemical conversion efficiencies in the range of 70% to 90%, which is highest among various alternative.
- Gasification output capacity, especially in the high output ranges, is controlled only by availability of adequate feed materials rather than technical consideration.
- The area requirement for gasification equipment is lowest per unit output of energy in the form of heat and/or electricity.
- The gasification equipment has high turn down ratios comparable to biogas and higher than steam turbine systems.

3. Gasifiers

The production of generator gas (producer gas) by gasification is partial combustion of solid fuel (biomass) which takes place at temperature of about 1000°C. The reactor is called a gasifier. The combustion products from complete combustion of biomass generally contain nitrogen, water vapour, carbon dioxide and surplus of oxygen. However in gasification where there is a surplus of solid fuel (incomplete combustion) the products of combustion are combustible gases like Carbon monoxide (CO), Hydrogen (H₂) and traces of Methane and non useful products like

Table 1. Significant differences between fixed bed and fluidized bed.

Fixed bed	Fluidized bed
(-) Higher investment (about 10%), two lines	(+) Lower investment
(-) Feedstock fines must be agglomerated	(+) No problems with feedstock fines
(-) Particle size as uniform as possible	(+) Broad particle size distribution
(+) Very great particle size possible (up to 100 mm)	(-) Limited Particle size (up to 50 mm)
(+) Nearly tar free gas	(-) Tar (1 g/m ³ n); high tar content in the gas
(+) High carbon conversion rate (90–99%)	(-) Low carbon conversion rate (90%)
(+) Discharge of liquid slag	(-) Ash fusion by low-softening ash

(+) indicates positive aspects; (-) indicates negative aspects

tar and dust. The key to gasifier design is to create conditions such that (i) biomass is reduced to charcoal and, (ii) charcoal is converted to CO and H₂ at suitable temperature to produce. Basically gasifiers are classified as fixed bed and fluidized bed type gasifiers similar to fixed bed or fluidized-bed systems in combustion technology. The significant differences concerned with these gasifiers are given below (Hindsgaul *et al* 2000) (table 1).

Since there is an interaction of air or oxygen and biomass in the gasifier, fixed bed gasifiers are classified according to the way air or oxygen is introduced in it. There are two types of gasifiers: downdraft and updraft. These are also called cocurrent and countercurrent, respectively (figure 1).

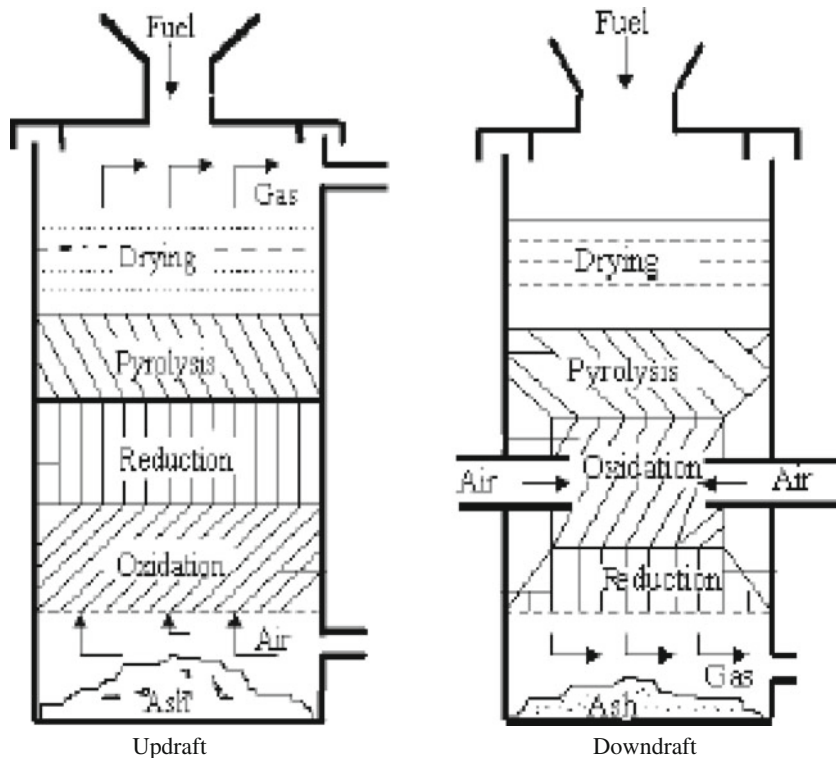
**Figure 1.** Updraft and downdraft gasifiers.

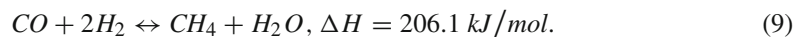
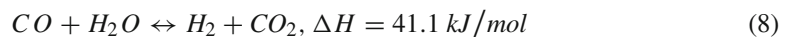
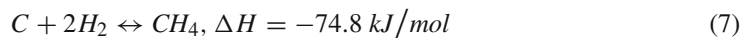
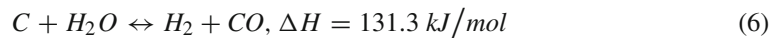
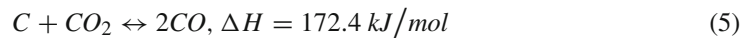
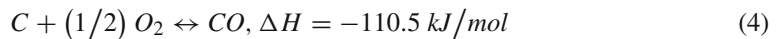
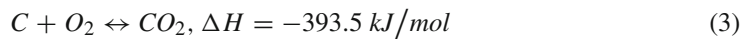
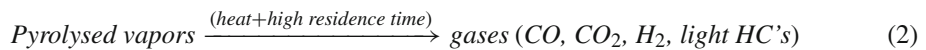
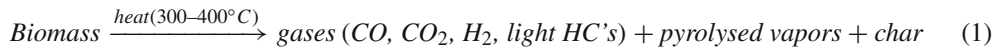
Table 2. Advantages and disadvantages of various fixed bed gasifiers.

S. No.	Gasifier type	Advantage	Disadvantages
1.	Updraft	Small pressure drop Good thermal efficiency Little tendency towards of slag formation	Great sensitivity to tar and moisture and moisture content of fuel Relatively long time required for start up of IC engine Poor reaction capability with heavy gas load
2.	Downdraft	Flexible adaptation of gas Production to load Low sensitivity to charcoal dust and tar content of fuel	Design tends to be tall Not feasible for very small particle size of fuel

And as the classification implies updraft gasifier has air passing through the biomass from bottom and the combustible gases come out from the top of the gasifier. Similarly, in the downdraft gasifier the air is passed from the tuyers in the downdraft direction. With slight variation almost all the gasifiers fall in the above categories. The fuel, its final available form, its size, moisture content and ash content, dictates the choice of one type of gasifier over other. The advantages and disadvantages generally found for various classes of gasifiers are listed in table 2.

3.1 Chemical reactions in the gasifier

Gasification is a highly complex chemical process. Bridgewater described the gasification sequence as drying and evaporating processes of biomass followed by pyrolysis, and finally oxidation and reduction (Bridgewater 2003). However, the overall process can be reasonably described by the reactions described below (Bridgewater 2003; McKendry 2002).



Among the reactions described above, the char-oxidation (Eq. 3) and partial-oxidation (Eq. 4) reactions are slowest, and consequently the rate controlling factor in the overall gasification

process (McKendry 2002). Pyrolysis also results in liquid which is resistant to the cracking due to temperature increase though most of the pyrolyzed liquid does so at higher temperature. This requires subsequent cleaning set-up for the tar, which can be a substantial investment in many cases (Bridgewater 2003).

3.2 Gasifier fuel characteristics

Almost any carbonaceous or biomass fuel can be gasified under experimental or laboratory conditions. However, the real test for a good gasifier is not whether a combustible gas can be generated by burning a biomass fuel with 20–40% stoichiometric air but that a reliable gas producer can be made which can also be economically attractive to the customer. Towards this goal the fuel characteristics have to be evaluated and fuel processing done.

A gasifier fuel can be classified as good or bad according to the following parameters.

3.2a Energy content and bulk density of the fuel: The higher the energy content and bulk density of fuel, the similar is the gasifier volume since for one charge one can get power for longer time (Livingston 2007; Ciolkosz 2010).

3.2b Moisture content: It is desirable to use fuel with low moisture content because heat loss due to its evaporation before gasification is considerable and the heat budget of the gasification reaction is impaired. Besides impairing the gasifier heat budget, high moisture content also puts load on cooling and filtering equipment by increasing the pressure drop across these units because of condensing liquid. Thus in order to reduce the moisture content of fuel some pre-treatment of fuel is required. Generally, the desirable moisture content for fuel should be less than 20% (<http://www.fao.org/docrep/t0512e/T0512e17.htm>).

3.2c Dust content: All gasifier fuels produce dust. This dust is a nuisance since it can clog the internal combustion engine and hence has to be removed. The gasifier design should be such that it should not produce more than 2–6 g/m³ of dust (Livingston 2007). The higher the dust produced, more load is put on filters necessitating their frequent flushing and increased maintenance (Warneck 2002; Ptasinski *et al* 2007).

3.2d Tar content: Tar is one of the most unpleasant constituents of the gas as it tends to deposit in the carburetor and intake valves causing sticking and troublesome operations. It is a product of highly irreversible process taking place in the pyrolysis zone. The physical property of tar depends on temperature and heat rate and the appearance ranges from brown and watery (60% water) to black and highly viscous (7% water). There are approximately 200 chemical constituents that have been identified in tar so far. A well-designed gasifier should put out less than 1 g/m³ of tar (Warneck 2002; Ptasinski *et al* 2007).

3.2e Ash and slagging characteristic: The mineral content in the fuel that remains in oxidized form after complete combustion is usually called ash. Ash basically interferes with gasification process in two ways:

- (i) It fuses together to form slag and this clinker stops or inhibits the downward flow of biomass feed.

- (ii) Even if it does not fuse together it shelters the points in fuel where ignition is initiated and thus lowers the fuel's reaction response.

Ash and tar removal are the two most important processes in gasification system for its smooth running. Various systems have been devised for ash removal. In fact some fuels with high ash content can be easily gasified if elaborate ash removal system is installed in the gasifier. Only two fuels have been thoroughly tested and proven to be reliable. They are charcoal and wood. Besides with the present energy crisis where most countries do not have enough supply of wood it is advantageous and attractive to use agricultural residues. For the agricultural sector this is an extremely attractive alternative (Rathore & Panwar 2009).

3.2f Biomass type: Biomass elemental composition has a significant effect on syngas composition. The release of pyrolysis gas is highly dependent on hydrogen/carbon ratio as well as oxygen/carbon ratio and increases when these ratios increase, especially with an increase in hydrogen/Carbon ratio. A higher oxygen concentration in biomass needs lower ER for gasification because of its inherent oxygen that will also be available for gasification (Mishra *et al* 2010).

4. Review of past experiments

A large number of researches were carried out with biomass as a replacement of internal combustion (IC) engine fuel by researchers from various parts of the world. Most of these experiments were reported from US, Europe, India, Malaysia, China and Germany. A summary of these experimental results is given below.

Vyarawalla *et al* (1984) have designed and developed a 9 kW capacity biomass-based gasifier engine system for laboratory experiments and a field trial of nearly 1000 h for saw dust and toor stalks as biomass. They could achieve the diesel saving up to 75% by compression ignition type engines by producer gas from gasifier. A topless wood gasifier running a 3.75 kW diesel engine pump set for water pumping was tested and developed for wood by Rajvanshi & Joshi (1989). It was found that to produce 1 kWh of energy 1.33 Kg of wood and 125 ml of diesel were used and also economic analysis reveals that with a Low (60%) diesel substitution, gasifier system is economically on par with a diesel only fuel.

Parikh *et al* (1989) have compared the performance of direct injected and indirect injected diesel engine running with producer gas from downdraft biomass gasifier. They used Subabool tree (*Leucaena leucocephala*) as a biomass sample. They achieved a diesel replaces of 68 to 80% at 80% of rated load by changing the volume of gas cooling – cleaning system. It has been established that dual fuel operation results in substantial increase in engine exhaust CO content more so at part load. Coffee husk as biomass for gasification was used to analyse the performance of diesel engine on dual fuel mode. It could achieve the maximum diesel replacement of 31% only. Krishna & Kumar (1994) suggested that this is due to clinkers formation and a low density of biomass. Jorapur & Rajvanshi (1997) suggested the commercial scale (1080 MJ/h) development of a low density biomass gasification system for thermal application. The gasifier can handle fuels like sugarcane leaves, bajra stalks, sweet sorghum stalks and bagasse, etc. From the results, it is demonstrated that low density biomass gasifier running on sugarcane leaves or bagasse can be successfully retrofitted to existing oil fired furnace/boilers in metallurgical and other industries, if the cost of biomass is less than Rs.1350 T⁻¹ for capacity of 1080 MJ/h.

Availability of eight selected agricultural residues as raw material for biomass gasification in India with due consideration to their seasonal and geographical availability dimensions were discussed by Tripathi *et al* (1998). Biomass residues of arhar stalk, maize stalk, maize cobs, cotton stalk, mustard stalk, jute and mesta sticks, rice husk and groundnut shells have been assessed. It is reported that more than eight million tonnes of these residues were produced in the year with a primary energy potential of about 1200 Peta Joules. Cost estimates of biomass residues vary from Rs. 132/tonne to Rs. 628/tonne, depending on the agricultural residue cost and the transporting distance. These cost figures were much lower than the prevailing cost of coal in India. Hence, these agricultural residues may be profitably used as feedstock in biomass gasification and briquetting plants.

Martin *et al* (1997) studied the gasification of wood from the mill, which is integrated with a combined cycle for power production, as well as with the fuel synthesis. This combination makes better use of the gasifier, since the synthesised gas can be used to generate excess electricity during the winter season when electricity prices are high, whereas it can be used to produce transportation fuels at other times. The criteria for comparison of fixed bed and fluidized bed gasifier were worked out as technology, use of material, use of energy, environment and economy. A utility analysis for thermo chemical processes are studied also shows fixed bed gasifier is the best in the plants having 10 MW_{th} capacity and also they have high carbon conversion rate (99%) as compared to fluidized bed gasifier with nearly tar-free gas (Warneck 2000). The usage of producer gas, a lower calorific gas as a reciprocating engine fuel at a high compression ratio (17:1) is technically feasible (Sridhar *et al* 2001). The effect of moisture on the various characteristics of gas produced from different biomass fuel has been investigated. They give the idea about carbon conversion, tar emission, product gas heating value and cold gas efficiency (Drift *et al* 2001).

Equivalence ratio plays an important role on the gas composition, calorific value and the gas production in downdraft biomass gasifier. Optimum equivalence ratio for the best performance of downdraft biomass gasifier comes out to be 0.38. Gas flow rate per unit weight of fuel increases linearly with equivalence ratio. The specific consumption of the biomass materials (furniture wood and wood chips) is found to be of the order of 2 kg/kWh, while the overall efficiency of the biomass electrical power producing system is of the order of 10–11% and the cold gas efficiency is of the order of about 80% (Zainal *et al* 2002). Feed rate also effects on Calorific value/composition of the product gas and the associated variations of gasifier zone temperatures (Dogru *et al* 2002). Optimum operation of the gasifier was found to be between 1.44 and 1.47 Nm³/kg of air fuel ratios at the values of 4.06 and 4.48 kg/h of wet feed rate which gives the producer gas with a good gross calorific value of about 5 MJ/m³ at a volumetric flow of 8–9 N m³/h product gas.

A gasifier has been fabricated in Sri Lanka for the tea industry. Experimental testing of the design under various conditions has produced data that has then been used to calibrate a computer program, developed to investigate the impact of design parameters and features of gasifier on conversion efficiency. It was concluded that a wood chip size of 3–5 cm with moisture content below 15% (dry basis) should be used in that gasifier. Feed material with a fixed carbon content of higher than 30% and heat losses of more than 15% should be avoided. For the above parameters, the gasification zone should be 33 cm long to achieve an acceptable conversion efficiency (Jayah *et al* 2003). Technical performance and sustainability of the largest biomass gasifier-based power plant (500 kW) in India has been reviewed with respect to diesel replacement, fuel wood supply, cost of electricity generation and environmental pollution. The overall

efficiency of that plant is about 19% and the diesel replacement obtained at the optimum load condition was 64% (Sonaton *et al* 2004). Concentration of pollutants such as carbon monoxide (CO), oxides of nitrogen (NO_x), sulphur dioxide (SO₂), hydrocarbons (HC) and particulates in the flue gas were monitored and emission factors have been derived using kikar wood as biomass fuel in downdraft biomass gasifier clubbed with dual fuel diesel engine. In addition to the emission characteristics, diesel replacement rate at different loads were estimated. The diesel engine is capable of running with dual fuelling with 67–86% diesel replacement rate. Also engine performance decreases with increase in emissions at part load conditions both at diesel and dual fuel mode. For optimum load condition (80% of the rated capacity) the emissions were generally below the emission norms except for carbon monoxide emission from dual fuel operation, which exceeds the standard due to combination of factors such as low heating value of gas, low adiabatic flame temperatures, and low mean effective pressures. Carbon monoxide emissions from dual fuel engines were higher than diesel engines at all operated load condition. Dual fuel operation reduces NO_x and SO₂ emission without increasing particulate emission (Uma *et al* 2004). It is reported that the higher capacity of the engine than the required capacity must be selected because the producer gas dual fuel engine could run only at a maximum of 50–60% of maximum load condition. The engine performance decreases with increase in emissions at part load conditions both at diesel and dual fuel mode of operation. At optimized conditions, the exhaust emissions are found to be closer irrespective of the fuel used. In the dual fuel mode of operation, while using wood chips higher diesel savings is achieved when compared to coir pith. The diesel replacement while using coir pith in the gasifier could be improved by briquetting (Ramadhas *et al* 2006).

Effect of woody biomass components on air-steam gasification were also investigated using the downdraft fixed-bed gasifier at 1173 K and at atmospheric pressure. The gasification conversions in cellulose, xylem and lignin were 97.9%, 92.2%, and 52.8% on a carbon basis, respectively. The product gas composition in cellulose were 35:5 mol% CO, 27:0 mol% CO₂, and 28:7 mol% H₂, and the CO compositions were higher than the CO₂ or H₂ compositions, which is similar to that in the Japanese Oak, of which the main component was cellulose. In contrast, the product gas compositions in xylem and lignin were approximately 25 mol% CO, 36 mol% CO₂, and 32 mol% H₂, and the CO composition is lower than the CO₂ or H₂ compositions, which were similar to those in Japanese red pine bark, of which the main component were lignin. The fundamental information obtained in the gasification of each component could possibly be used to predict the composition of product gas generated in air-steam gasification of different woody biomass (Hanaoka *et al* 2005). The fuel properties of *Jatropha* seed husk and its gasification feasibility is investigated for open core down draft gasifier. Performance is evaluated in terms of fuel consumption rate, calorific value of producer gas and gasification efficiency at different gas flow rates. Producer gas calorific value and concentration of CO, along with gasification efficiency, increased with the increase in gas flow rate. The maximum gasification efficiency is found to be 68.31% at a gas flow rate of 5.5 m³/h and specific gasification rate of 270 kg/ m² h which is comparable to that of wood (Vyas & Singh 2007). In dual fuel mode (fossil diesel, FD + producer gas), the concentration of pollutants like carbon monoxide (CO), carbon dioxide (CO₂), nitric oxide (NO), nitrogen dioxide (NO₂) reduced by 55%, 19.7%, 82% and 83%, respectively, while hydrocarbon (HC) increased by 67.2% as compared to FD. Operated in dual fuel mode of (FD+ refined rice bran oil, RRBO), the concentration of pollutant like CO, CO₂ and HC reduced by 60%, 0.86% and 91%, respectively whereas NO_x increased by 23.48% as compared to FD. In mixed fuel mode (pre-heated blends of RRBO+FD in the

proportion of 3:1 and producer gas) the concentration of pollutants like HC, NO and NO₂ reduced by 48.28%, 61.57% and 80.48%, respectively, while CO increased by 16.31% as compared to FD (Singh *et al* 2005, 2007). Engine has also been run with diesel, rubber seed oil, diesel + coir pith and rubber seed oil + coir pith combinations. The engine performance decreases in dual mode operation with diesel or rubber seed oil as pilot fuel. The pilot fuel consumption of rubber seed oil is higher than that of diesel in dual fuel mode operation. Carbon monoxide emission of rubber seed oil-producer gas operation is higher than diesel-producer gas operation under all load conditions because of higher fuel consumption with lower calorific value fuels. Moreover, higher carbon dioxide emissions are observed with rubber oil-producer gas operation. Also exhaust emissions were found to be closer irrespective of the fuel used (Sridhar *et al* 2001). Brake thermal efficiency values of 24.25%, 22.25% and 23% were obtained with producer gas–diesel, producer gas–Honge oil and producer gas–Honge oil methyl ester, respectively. In dual fuel operation emissions like smoke and NO_x were reduced whereas CO and HC increased considerably (Banapurmath & Tewari 2009).

The increase of oxygen content in fuel blend increased the Brake specific fuel consumption of engine. The more oxygenated fuel is added in the fuel, the more reduction is achieved in smoke and particulate matter (PM) while slight increase in NO_x is witnessed (Chen *et al* 2008). Effects of air flow rate and moisture content on biomass consumption rate and quality of the producer gas generated is evaluated in terms of equivalence ratio, producer gas composition, calorific value of the producer gas, gas production rate, zone temperatures and cold gas efficiency. Biomass consumption rate decreases with the increase in moisture content of biomass while increase as there is increase in the air flow rate. Molar fraction of N₂ and CO₂ decrease till equivalence ratio (ϕ) = 0.205, and for higher values of ϕ , they increase. The fraction of CO and H₂ shows exactly opposite trend to that of N₂ and CO₂. The calorific value, pyrolysis zone temperature and the oxidation zone temperature is maximum at ϕ = 0.205. However, the calorific value decreases for an equivalence ratio ranging from 0.205 to 0.35. The production rate of producer gas continuously increases with an increase in ϕ . The value of cold gas efficiency 0.25 is almost double as ϕ = 0.17 changes to 0.035. The effect of ϕ on cold gas efficiency is comparatively lower for higher values of ϕ . For the downdraft biomass gasifier optimum equivalence ratio is 0.205 (Sheth & Babu 2009).

A one-dimensional stationary model of biomass gasification in a fixed bed downdraft gasifier was based on the mass and energy conservation equations and includes the energy exchange between solid and gaseous phases, and the heat transfer by radiation from the solid particles was proposed. The proposed model is used as tool to study the influence of process parameters, such as biomass particle mean diameter, air flow velocity, gasifier geometry, composition and inlet temperature of the gasifying agent and biomass type, on the process propagation velocity (flame front velocity) and its efficiency. The maximum efficiency was obtained with the smaller particle size and lower air velocity (Tinaut *et al* 2008). Combustible gas production from biomass materials such as coconut shell, groundnut shell and rice husk were experimentally investigated at 800°C using gasification technique by a downdraft gasifier. The calorific value of coconut shell is 23.01% higher than ground nut shell and 45.45% higher than rice husk. Hydrogen amount in the producer gas for ground nut shell is more than coconut shell and rice husk. But carbon monoxide is 17.55% and 21.22% higher than ground nut shell and rice husk as compared to coconut shell. Also 6.15% and 38.71% methane are more in coconut shell as compared to other tested biomass. The coconut shell have more carbon content also in producer gas. Coconut shell is the best suitable fuel for gasifier compared to the other two biomass materials (Sivakumar & Krishna 2010).

4.1 Advantages

From the review of literature available in the field of biomass usage, many advantages are noticeable. The following are some of the advantages of using biomass as fuel with diesel in I.C. engine in India (Tewari 1999; Sheng 1989).

- India is an agriculture-based country so agricultural waste obtained domestically helps to reduce costly petroleum imports.
- Development of the biomass usage machinery would strengthen the domestic, and particularly the rural, agricultural economy of agricultural based countries like India.
- It is biodegradable and non-toxic.
- It is a renewable fuel that can be made from agricultural crops and or other feed stocks that are considered as waste.
- It contains no aromatics.
- It has a reasonable cetane number and hence possesses less knocking tendency.
- Environment friendly due to absence of sulphur content.
- No major modification is required in the engine.
- Personal safety is improved (flash point is higher than that of diesel).
- It is usable within the existing petroleum diesel infrastructure (with minor or no modification in the engine).

4.2 Challenges

The major challenges that face the use of Biomass as I.C. engine fuels are listed below (Kohli & Ravi 2003; Bridgewater 1995; Sheng 1989).

- The price of biomass is dependent on various factors like availability, transportation, and drying, etc.
- Feed stock homogeneity, consistency and reliability are questionable.
- Storage and handling is difficult (particularly stability in long term storage).
- Flash point in blends is unreliable.
- Compatibility with I.C. engine material needs to be studied further.
- Acceptance by engine manufacturers is another major difficulty.
- Continuous availability of the particular type of biomass needs to be assured before embarking on the major use of it in I.C. engines.

4.3 Technical difficulties

The major technical areas (with respect to the use of biomass as fuels in I.C. engines), which need further attention are listed below (Kohli & Ravi 2003; Bridgewater 1995; Sheng 1989).

- Development of less expensive quality tests.
- Emission testing with a wide range of biomass feed stocks.
- Studies on developing specific markets such as mining, municipal water supplies, etc. which can specify bio-diesel as the fuel choice for environmentally sensitive areas.
- Co-product utilization like ash produced in a beneficial manner.
- Efforts to be focused on responding to fuel system performance, material compatibility and low fuel stability under long term storage.

- Continued engine performance, emissions and durability testing in a variety of engine types and sizes need to be developed to increase consumer and manufacturer confidence.
- Environmental benefits offered by biomass over diesel fuel needs to be popularized.
- Studies are needed to reduce cost and identify potential markets in order to balance cost and availability.

5. Conclusion

Researchers in various countries carried out many experimental works using producer gas derived biomass as I.C. engine fuel substitutes. These results have shown that thermal efficiency was comparable to that of diesel with small amounts of power loss while using producer gas. The particulate emissions of producer gas are lesser than that of diesel fuel with a reduction in NO_x and producer gas from biomass gave performance characteristics comparable to that of diesel. Hence, they may be considered as diesel fuel substitutes. The use of producer gas derived from biomass as I.C. engine fuels can play a vital role in helping the developed world to reduce the environmental impact of fossil fuels.

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Power generation using cotton stalk-derived producer gas in diesel engines

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ABSTRACT

In this study, the potential of cotton stalks as feedstock for a gasifier is analyzed. The emissions and performance characteristics of the gasifier–engine system is analyzed by running the engine at different loads. These characteristics of the dual fuel diesel engine are compared to those under different load conditions. Specific fuel consumption in the dual fuel mode of operation is favorable at all load conditions. CO emissions are much higher in the case of the dual fuel (diesel + gas) mode of operation as compared to that of diesel-only mode, and the level of NO_x emissions is drastically reduced in the case of dual fuel mode.



KEYWORDS

Biomass; biomass gasification; diesel engine; dual fuel operation; gasifier

Introduction

In India's present energy scenario, demand for energy increases continually (Table 1). Environmental concerns and reduction of fossil fuel reserves have led to extensive searching for alternate fuels. The recent rise in fuel prices has affected economic activity and has worsened the global energy scenario. Generation of electric power using biomass resources is presently receiving more attention globally. Biomass as a source of energy not only reduces the reliance on imported oil, but may also benefit the environment by reducing emissions of greenhouse gases and pollutants that affect air quality. Biomass is a renewable energy resource derived from the carbonaceous waste of various natural activities. It is derived from various sources, including agricultural crops, raw forest materials, and clean municipal and industrial wastes. The Ministry of New and Renewable Energy (MNRE, 2013), Govt. of India has estimated that about 600 Mt of crop residues are generated every year in India. "Biomass Power", the Government of India's national program on biomass, aims at the optimum application of a variety of biomass sources such as agro-based residues for power generation through the state-of-the-art conversion technologies of combustion, pyrolysis, gasification, etc.

Biomass gasification is among biomass conversion technologies recently developed in order to produce a combustible gas mixture (called producer gas) using agro-residues. Producer gas obtained by partial combustion of biomass in a gasifier can act as a favorable renewable and alternative fuel for both spark ignition (SI) and compression ignition (CI) engine application. The advancement of gas engines using producer gas has been examined ever since World War II. It is estimated that over 7 million spark ignition engine vehicles in Europe, Australia, South America, and the Pacific Islands were converted to run on producer gas during World War II. Parikh et al. (1989) compared the performance of direct and indirect injected diesel engines operating with producer gas from a downdraft biomass gasifier, using the Subabool tree as a biomass sample. They achieved a diesel replacement of 68–80% at 80% of rated load by changing the volume of the gas cooling–cleaning system. It is recognized that dual fuel operation results in a substantial

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Table 1. Five-year energy planning (Ministry of Power, 2013).

5-year Plan	Demand (MW)	Installed Capacity (MW)	Shortage (MW)
6 th (1980–85)	52,000	47,000	5,000
7 th (1985–90)	75,000	65,000	10,000
8 th (1990–92,92–97)	1,05,000	85,000	20,000
9 th (1997–2002)	1,32,000	1,05,045	26,955
10 th (2002–007)	1,46,000	1,32,329	13,671
11 th (2007–012)	2,12,200	1,99,877	12,323

increase in engine exhaust CO content, more so at part loading. Jorapur & Rajvanshi (1997) suggested the commercial-scale (1,080 MJ/h) development of a low-density biomass gasification system for thermal utilization. Their gasifier could handle fuels such as sugarcane leaf, bajra stalk, sweet sorghum stalk, and bagasse, etc. They established that a low-density biomass gasifier running on sugarcane leaf or bagasse can be successfully modified to existing oil-fired furnace/boilers in metallurgical and other industries, providing the biomass cost is less than Rs.1,350 T⁻¹ for a capacity of 1,080 MJ/h. Martin et al. (1997) examined the gasification of wood from a mill, which was mixed in a combined cycle for power production, in addition to fuel synthesis. This combination was found to make better use of the gasifier, since the producer gas could be used to develop excess electricity during the winter season when electricity prices are higher, whereas it can be used as transportation fuel at other times. Sridhar et al. (2001) discussed the application of producer gas in a reciprocating engine fuel at a 17:1 compression ratio. From their study it was established beyond doubt that the running of an engine using producer gas in SI mode at higher compression ratio is technically feasible. Ramadhas et al. (2006) analyzed the potential of coir pith and wood chips as the feedstock for a gasifier. That study proved that an engine power higher than that required must be selected, because a dual fuel engine run with producer gas achieved only at 50–60% diesel replacement under maximum load condition. They also suggested that greater diesel saving is achieved using wood chips as compared to coir pith in the dual fuel mode of operation (Malik et al., 2009; Malik and Mohapatra, 2013; Singh et al., 2005, 2007; Sivakumar and Krishna Mohan, 2010; Uma et al., 2004).

Previous literatures document work on biomass gasification of wood chips only. In the present study, the potential of cotton stalk as feedstock for the gasifier is analyzed.

Characterization of the biomass used

Wood is commonly used as traditional biomass wherever heat generation is required. It is well known as a suitable biomass fuel because of its superior calorific value and inferior ash content. The key properties of cotton stalk in comparison with other biomasses are listed in Table 2.

Experimental methodology

A simplified layout of the gasifier–engine experimental system is shown in Figure 1. The experimental setup includes a diesel engine, biomass gasifier, gas filter, gas cooler, and eddy current dynamometer. The biomass is fed through the feed door and is stored in the hopper. The throat (or

Table 2. Characterization of fuels.

Biomass	Ash %	C%	H%	N%	O%	S%	Calorific value (MJ/kg)
Cotton stalks	6.68	43.64	5.81	0	43.87	0	17.4
Bagasse	4.27	44.80	6.20	0.20	44.40	0.01	18.11
Rice husk	17.60	38.30	4.80	0.34	35.45	0.03	14.4
Rice straw	10.70	42.30	5.60	0.90	40.50	0.02	11.7
Wood chips	3.20	48.60	5.56	0.60	41.46	0.03	17.4

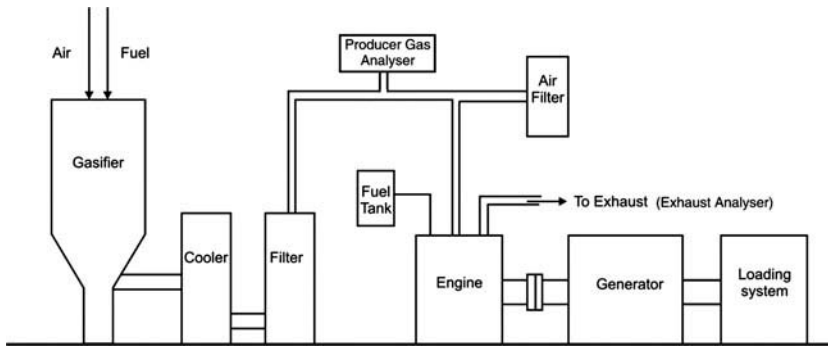


Figure 1. Schematic arrangement of experimental setup.

Table 3. Specifications of engine used.

Make	Kirloskar
Type	Single-cylinder, Four-stroke, Water-cooled Diesel Engine.
Rated Power	3.5 kW
Speed	1,500 rpm
Loading device	Eddy current dynamometer

hearth) ensures relatively clean and good quality gas production. The grate holds charcoal for reduction of partial combustion products while allowing the ash to drop into the ash collection cone. The gas outlet is connected to the engine via a Venturi scrubber, separator box-cum-fine filter, and check filter with an air control valve to facilitate running of the engine in dual fuel mode. Partial combustion of biomass in the gasifier generates producer gas, which then enters the gas cooler. Dust particles in the gas are removed by passage through the gas filter. The valves are arranged in the appropriate section of gas and airflow to control the gas. An orifice meter is used to measure gas flow rate separately. A “Kirloskar” single-cylinder, water-cooled, direct injection, four-stroke diesel engine is used for power generation. The detailed specification of the engine is given in Table 3.

Performance and emission analysis were carried out in diesel mode and dual fuel mode under various load conditions. The dual fuel mode was carried out by supplying the gas–air mixture to the combustion chamber of the engine through the inlet manifold. With the rotation of gas valves, the amount of air or gas entering the engine can be varied, creating variation in the air–fuel mixture. The air–fuel ratio reduces with increase in gas flow in all cases. A HORIBA gas analyzer was used to measure the concentration of exhaust gas emissions from the HC & flue gas analyzer (KM9106) for CO and NO_x. Exhaust gas temperature was measured by thermocouple. A data acquisition system was used to record the all required parameters during the experiment. Gas samples for gas chromatography were taken from the orifice meter port.

Results and discussion

The gas composition determined by gas chromatography is shown in Table 4. This parameter plays a vital role in the detailed analysis of engine performance.

Table 4. Composition of gas produced from gasifier.

Gas	%
Methane	48.7
Carbon Monoxide	0.03
Carbon Dioxide	1.65
Hydrogen	3.95

Brake thermal efficiency

The brake thermal efficiency of the dual fuel engine is higher than that of the diesel, as shown in Figure 2. A maximum brake thermal efficiency of 24.02% was achieved in diesel mode, while in the dual fuel mode of operation the maximum brake thermal efficiency was of 43.05% at 10 kg load using cotton stalk. This is due to the higher content of methane in the gas produced from the gasifier.

Specific fuel consumption

Figure 3 shows the specific fuel consumption for diesel and dual fuel modes using producer gas and diesel. The percentage of savings using cotton stalk is higher than that of diesel (by 52%) throughout the operating range of the engine. At low load operation there is insufficient oxygen to complete combustion, which results in lower diesel saving.

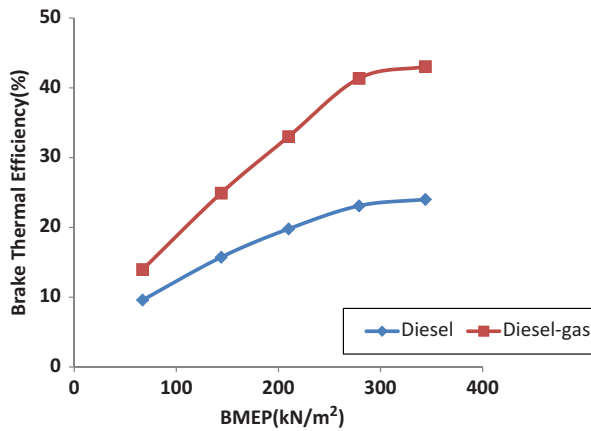


Figure 2. Brake thermal efficiency of engine w.r.t. BMEP.

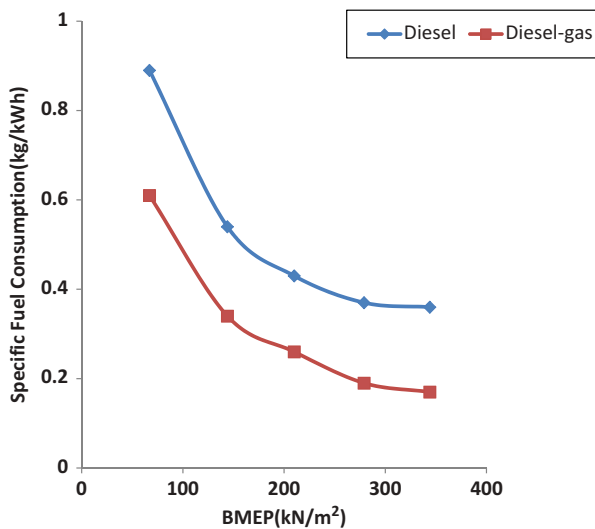


Figure 3. Specific fuel consumption of engine w.r.t. BMEP.

Carbon monoxide emissions

The range of carbon monoxide emissions with various mixtures of diesel and producer gas is shown in Figure 4. With increased percentage of gas flow an increase in carbon monoxide emission was observed, and was always much higher than that of diesel under all operating conditions. The higher concentration of CO emissions in dual fuel mode indicates incomplete combustion. The combination of producer gas–air flow to the engine reduces the amount of oxygen required for complete combustion; this constitutes incomplete combustion and results in an increase in CO emissions.

Nitrous oxide

The variation in nitrous oxide emissions of the engine with various mixtures of diesel and producer gas is shown in Figure 5. With increase in percentage of gas flow, decrease in nitrous oxide emission was observed and was always much lower than that of diesel under all operating conditions.

Conclusions

Some important decisions on the engine performance and environmental aspects of electric power generation in the dual fuel mode of operation while using cotton stalk in the gasifier are highlighted in the present paper. This study proved that a diesel engine can run successfully in dual fuel mode of operation with a suitable biomass in the gasifier. The key conclusions are listed below.

- (i) The brake thermal efficiency of the dual fuel engine improved by 40% as compared to diesel, due to the higher methane content in the producer gas.
- (ii) Diesel consumption was reduced by 50% with dual fuel when producer gas from cotton stalk was used with diesel, in comparison to diesel only.

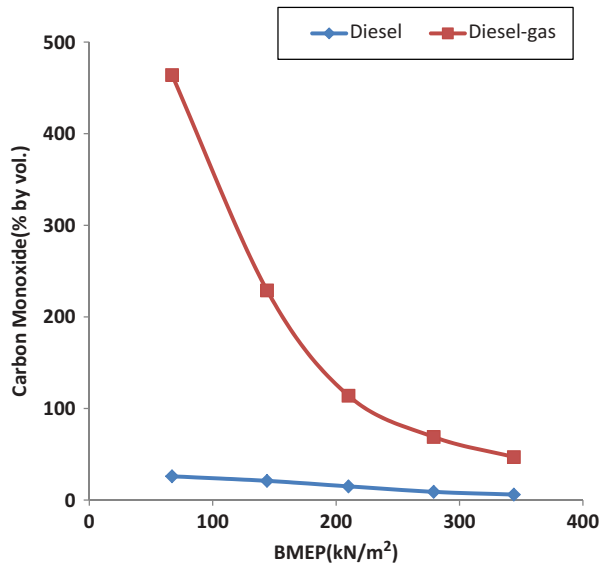


Figure 4. Carbon monoxide emissions of the engine w.r.t. BMEP.

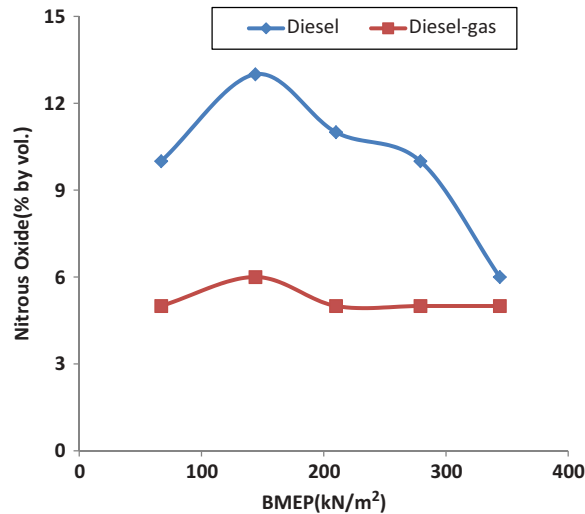


Figure 5. Nitrous oxide emissions of the engine w.r.t. BMEP.

- (iii) Carbon monoxide emissions in the dual fuel mode of operation were higher than when diesel alone was used under all load conditions, but the nitrous oxide level was much lower in dual fuel mode.

Waste/low-cost biomass feedstocks are applicable for producer gas generation. Hence, the power generation cost while using biomass is much cheaper than the traditional power generation cost. Agricultural waste materials like cotton stalk are suitable with little or no modification to the gasifier. A captive power generation plant can be installed depending on the availability of local biomass.

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