Study of Performance Characteristics and Noise of Dual Fuel Engine Run on Diesel and Producer Gas Produced from Cotton Stalk

A Dissertation

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Master of Engineering

In

Thermal Engineering

By

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Certificate

I hereby declare that the thesis entitled, **"Study of Performance Characteristics and Noise of Dual Fuel Engine Run on Diesel and Producer Gas Produced from Cotton Stalk"** is an authentic record of my work carried out as requirements for the award of the degree of Master of Engineering in Thermal Engineering at Thapar University, Patiala, under the supervision of **Dr S.K. Mohapatra**, HOD, Mechanical Engineering Department, Thapar University, Patiala during July, 2014 to July, 2016. No part of the matter embodied in this report has been submitted to any other university or institute for the award of any degree.

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Dedication

I dedicate this project to my **Great Master,** my creator, my strong pillar, my source of inspiration, wisdom, knowledge and understanding. He has been the source of my strength throughout my life and teaches me the real purpose of life and way of living it at every step and to my parents **Mr. Jagdev Singh** and **Mrs. Baldev Kaur** for their continuous motivation, support and moral help.

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Abstract

The current trend of energy consumption, in which fossil fuel is the main energy provider, has reached a level where other resources must be unearthed to ensure there is a constant supply for utilization. The rise in fuel prices recently has affected economic activity and only worsens the global energy scenario. Electricity generation is possible in new applications like biomass gasification. Among the all possible gasifiers, fluidized bed gasifiers are very appropriate in much respect. As major occupation of people in Punjab is agriculture. So a major source of biomass comes from this field. For this experiments are performed by taking sample of biomass i.e cotton stalk. A 3.5 kW, single cylinder, modified dual fuel compression ignition engine was fired with blend of diesel and the producer gas derived from processed cotton stalks at a constant speed of 1500±5 RPM. The investigation was carried out at a constant compression ratio of 18. The modified dual fuel compression ignition engine showed a smooth working at all load values in dual fuel as well as pilot fuel mode. In the investigation, it was observed that on dual fuel mode, a maximum of 45% of diesel was replaced by the producer gas and subsequently the cost of operation also decreases, with a slight reduction in the net power output. Reduction in power output is compensated by the considerable decrement in cost of power generation process. The engine was also tested for noise investigation on both pilot fuel mode as well as dual fuel mode. The dual fuel mode operation shows a significant increase in the cylinder pressure in comparison to the pilot fuel mode operation. Due to this increase in the cylinder pressure, a slight increase of 3.4 dB in the noise characteristics of the dual fuel engine was observed. The maximum noise of 92.1 dB was observed at ~80% load. This noise was further suppressed to 91.7 dB at 100% load. Some of the research papers based on factors effecting producer gas production are also presented in report. From the experimental study it is clear that the cotton stalk stands out to be the better fuel option for power generation purpose. With a wide range of applications the gasifier arrangement has a great potential to reduce the gap between energy requirement and supply of energy.

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Nomenclature

- CV - -Calorific Value
- CW – Carpentry Waste
- DFCI – Dual Fuel Compression Ignition
- FC – Fixed Carbon
- GHG – Green House Gas
- ICE – Internal Combustion Engine
- LPH – Liters Per Hour
- RES – Renewable Energy Sources
- VCRE – Variable Compression Ratio Engine
- VM – Volatile Matter

Chapter 1 Introduction

A large population in the world is still lacking the basic energy needs, even in 21st century. This is main problem 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 several others. The major reason for this problem is that hefty part of the residents is spread in locales – in villages and hamlets (Elliott 2007). The establishment of centralized grid in these nations is expensive due to distant inaccessible locations. Problem is further enhanced due to lack of strong economical structure to import oil for power production. Further, utilization of fossil fuel is strained to reduce GHG due to the ecological considerations. This is the major reason for the nations to shrink the utilization of fossil fuel and espouse appropriate renewable energy mechanism (Murphy et al. 2014; Holmgren et al. 2014; Kothari et al. 2014).

In view of new upcoming technologies, biomass has begun to look capable in the present renewable energy scenario which is ruled by solar, wind and micro/minihydel (Khalil et al. 2010). India is also an oil-importing nation and 70% of its Indians reside in half a million villages and hamlets across the nation which are loaded with bio-resources and are perfectly appropriate for biomass-based energy production technologies (Zhu & Zhuang 2012). Due to worldwide expectations of sustainable energy and diminution in the emanation of greenhouse gases, it is necessary to pay attention to biomass as an energy resource. Biomass is passive, so far as compared to fossil fuels. The large fraction of world's overall energy consumption is contributed by fossil fuels. According to the World Energy Assessment report 2015, 78% of the world's primary energy consumption is contributed by fossil fuel, 19% by renewable (out of which biomass contributes 9%). On the other hand, in India renewable sources contribute a very part to total energy production (just 8%) as shown in figures 1 and 2 (IEA 2015). The renewable energy part can be increased significantly by raising biomass utilization for power production as it is available in abundance at low costs.

A huge number of residents in India are reliant on agriculture as their source of income. Due to this a huge number of cattle and livestock are also present in India (Wint & Robinson 2007). Therefore Indian villages have the potential of availability of diverse types of biomass.

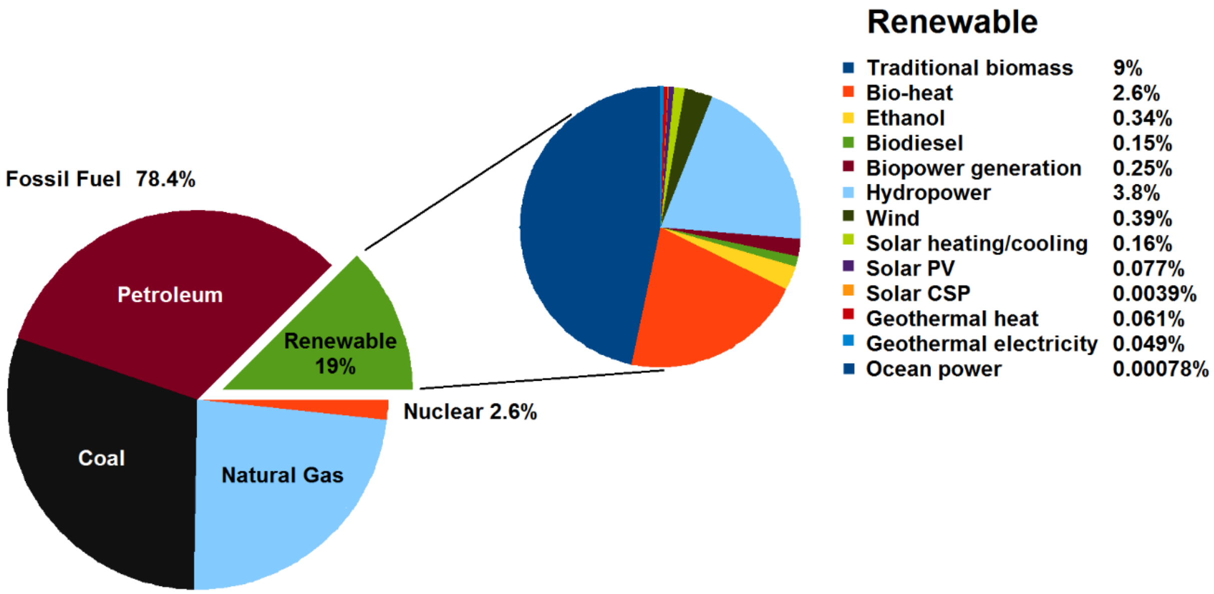

Fig 1 Total world energy consumption by source 2015 (Perez et al. 2012)

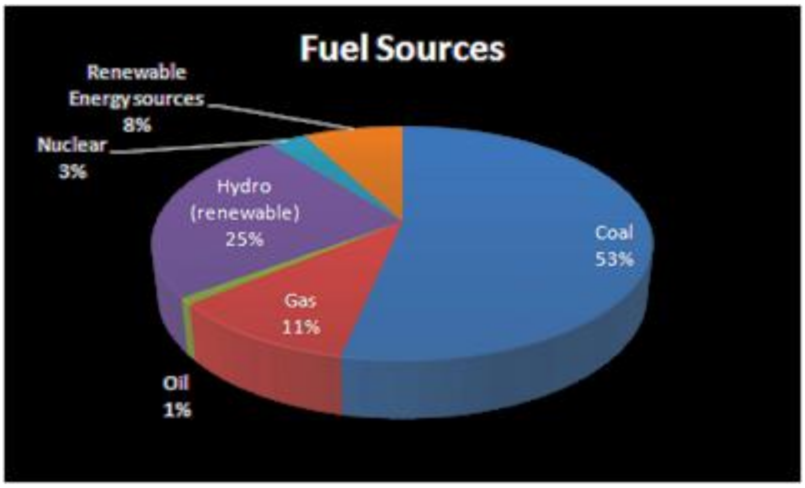

Fig 2 Energy and Nuclear Energy Scenario in India (Koroneos & Lykidou 2011)

Crops that can be utilized for energy are cotton stalks, sugarcane, corn, sugar beets, grains and many others. There are many factors, which decide suitability of a crop for energy use (Sims et al. 2006). The core material properties of concern while consequent processing as an energy source are: ratio of fixed carbon and volatiles, calorific value, ash/ residue content, alkali metal part, and cellulose/lignin ratio, moisture content (García et al. 2013). The biomass conversion processes can be classified as wet biomass conversion and dry biomass conversion processes (Damartzis & Zabaniotou 2011).

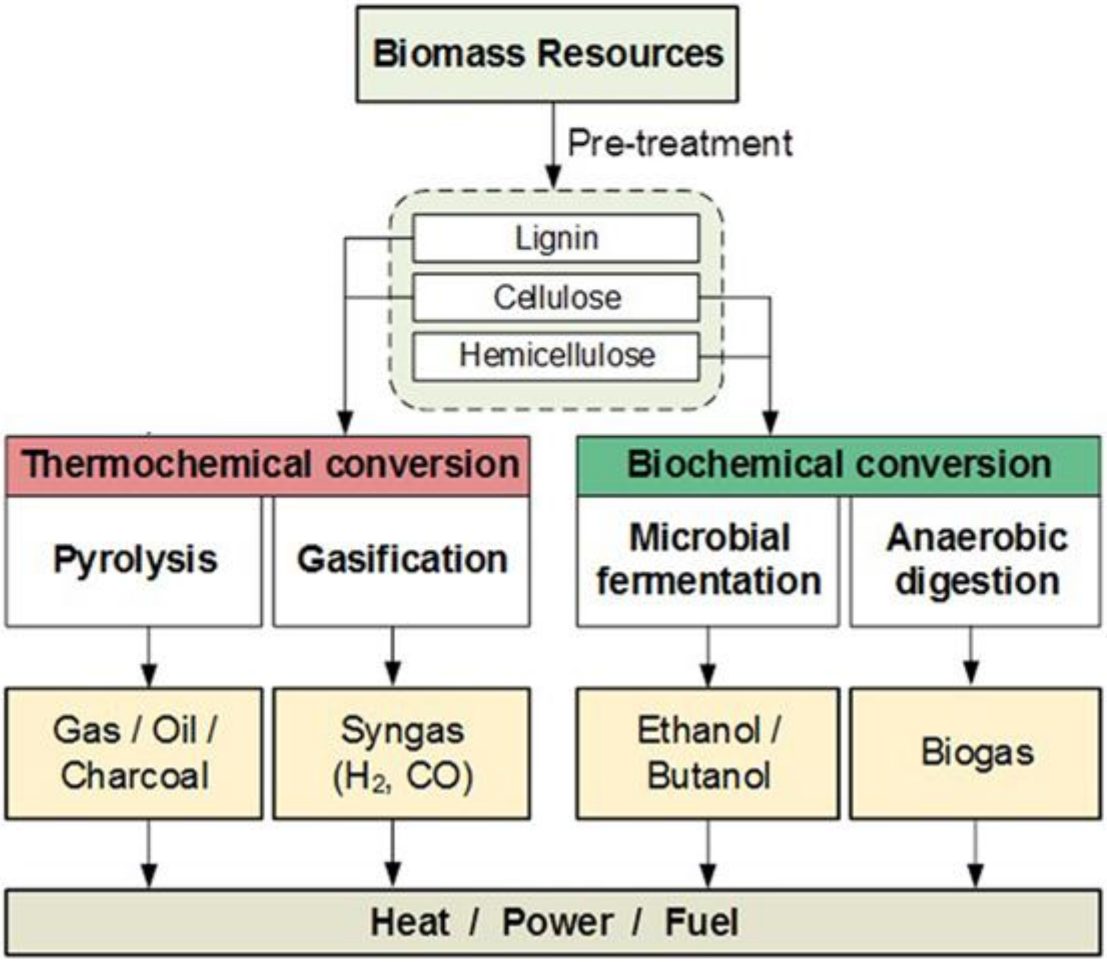

Fig 3 Biomass conversion processes (Kucuk & Demirbas 1997)

We all are familiar with biochemical route, for example, fermentation in the presence of enzymes and microorganisms. These processes occur in the absence of oxygen and don't involve external heat supply. But the main back draw of these processes is their slower processing rate (Schiel-Bengelsdorf et al. 2013). On the other hand thermo chemical processes proceed fast and have lot of potential to use biomass as an energy source (Panwar et al. 2012). A basic requirement of thermo chemical processes is a source of heat to carry on the chemical reactions. Obviously they are fairly faster than biochemical process and are easy to control. So emphasis is given on thermo chemical processes in the further report.

Now let us take an overview of main thermo chemical processes:

- **Combustion**

Conversion of biomass into carbon dioxide and steam in abundant air at high-temperatures is termed as combustion. Combustion involves exothermic reaction between the hydrocarbon present in biomass and oxygen. It is not an efficient way to use biomass due large amount of ash production and pollutants (Turns 2000).

- **Pyrolysis**

Thermal decomposition of biomass into gaseous, liquid and solid byproducts is termed as Pyrolysis. Unlike combustion, pyrolysis occurs in complete absence of oxygen. But in some cases partial combustion is permitted to give the thermal energy required for process to occur at faster rate (Basu 2013).

- **Liquefaction**

Liquefaction of biomass into liquid product which is easy to use as compared to solid biomass can be attained by gasification, pyrolysis or through the hydrothermal process. In hydrothermal process, biomass is transformed into an oily liquid product by placing the biomass with water at high temperatures ranging from 300°C to 350 °C under high pressure (12–20 MPa) for a period of time (Behrendt et al. 2008).

- **Gasification**

In Gasification process biomass is converted into producer gas by incomplete combustion of biomass. The gasification process occurs in three stages. First is drying, where intrinsic moisture content of biomass is decreased below a limit of 20%. Then pyrolysis occurs in which volatile gases get released. In the end gasification process occurs in which residues and volatiles are partially oxidized (Kirubakaran et al. 2009). Biomass Gasification makes it easy to use biomass as a fuel for power generation as it is easy to store, can be burnt in IC engines easily.

Producer gas is CO_2 neutral and its use as a fuel liberates lower quantities of harmful emissions such as sulfur dioxide and nitric oxide (Munir et al. 2010). In the further study whole emphasis is laid on usage of biomass as a fuel by gasification technique.

Chapter 2 Literature review

Basic Components of Gasification Process:

2.1Biomass:

All organic materials mainly of plant and animal origin which are combustible in nature present in land or aquatic environments are termed as biomass. The term biomass also include by-product and agricultural wastes, residues of farming and processing industries like bark, cobs, stalks, leaves, fruits, husk, cutting vines, straw etc. Municipal wastes, cattle refuses and plant products are also included in biomass category. Generally biomass materials are biodegradable and non-fossilized in nature (Christian 2000).

The main two categories of biomass are: wettable or wet biomass (starches, manures and molasses) and dry biomass (agricultural and woody materials and crop residues). Wet biomass is suitable for biological processes which occur at room temperature. On the other hand biomass having less moisture content (dry biomass) is best suited for thermal processes (van Rossum et al. 2009).

Biomass is composed of main five chemical elements (Boe & Beck 2008):

- Cellulose
- Hemicelluloses
- Lignin
- Organic components
- Inorganic components

The fibrous part of biomass which is non starchy in nature is called lingo-cellulose. The main characteristic of ligno-cellulose is that it is not included in human food chain and hence, its utilization for power production through gasification process does not pressurize the world's food supply. Agricultural biomass wastes such as stalks, straw, woody plant, husk, cereal plants, etc are rich in ligno-cellulose (Rajulu et al. 2002). Hence the biomass material obtained from fields is best suited for gasification process. As Punjab is an agricultural state, so it has large availability of such type of biomass and hence great potential for power production through biomass gasification.

2.1.1 Major sources of biomass are (Gokcol et al. 2009):

- Biological- Animal wastes, aquatic species etc
- Forestry biomass- Saw dust, wood wastes, bark etc
- Agricultural biomass- Rice husk, groundnut shells, coconut shells, pine bark, mustard sticks, cotton stalks and many more.
- Municipal wastes- Sewage sludge, vegetable and fruit peels, paper wastes etc.

2.1.2 Properties of Biomass:

Efficient working of gasifier depends on number of biomass properties. Gasification process gives best outputs in a specific range of values of each property (Wu et al. 2011). The major properties which effect gasification process are discussed below.

- **Energy content of fuel**

The common way to obtain Energy content of fuel is by using constant volume adiabatic bomb calorimeter. It gives higher heating values in which heat of condensation of water produced during combustion of fuel is included. For gasification process a fuel with high calorific value is required as it leads to production of high CV producer gas. Fuels with high energy content are preferred. Generally biomass fuels such as wood, agricultural wastes have heating value between10-15 MJ/kg (Saxena et al. 2009).

- **Moisture content**

Percentage of moisture in a biomass material depends on factors such as its origin and pre-treatment before gasification process. Total of inherent moisture and surface moisture is the moisture content of a fuel. Moisture content is generally measured by weight and should be less than 25% for efficient gasification. It is difficult to ignite fuel with high moisture content and also higher moisture contents causes reduction in the thermal efficiency of gasification process due to production of low calorific value gas as a part of energy produced is consumed in driving content off. This leads to lack of energy required for reduction reactions (Samuelsson et al. 2006).

- **Ignition temperature**

A reaction can be made self sustainable only if its temperature is above the ignition temperature of the fuel. So It is an important parameter which decides the ease of proceeding a gasification reaction. Materials having more volatile content have low ignition temperatures. Limited combustion is necessary in gasification process to provide energy for reduction reactions and pyrolysis so that reaction can be carried out at good pace. Since agricultural wastes are rich in volatile matter, they are easy to ignite and are good option for gasification (Jones et al. 2015).

- **Particle size and distribution**

Power required to draw gas and air out of gasifier and pressure drop across the gasifier depend on particle size of biomass. Fluffy and fine grained biomass materials can cause flow problems in the throat area of gasifier and cause increase in dust content of gas. On the other hand large particle size leads in reduction of reactivity of fuel which causes startup problems and reduces pace of reaction hence low yields of gas. In case of updraft gasifier channeling problem occur if too large particle size fuel is used for gasification (Guo et al. 2012). Due to above problems only a narrow range of particle size is Acceptable for gasification process. Generally biomass having particle size ranging between 4 to 25mm is ideal for gasification process. Due to particle size constraints agricultural need to be processed properly before using as a fuel in gasifier (Vaezi et al. 2013).

- **Bulk density of fuel**

Weight per unit volume of loose biomass particles is called bulk density of fuel. Mainly it depends on the particle size of fuel and moisture content of the biomass. Size of hopper of gasifier depends on bulk density of the fuel used and also on the manner of loading. Gasification process parameters such as gas yield, velocity of fuel and residence time of fuel in chamber are highly influenced by bulk density. Considerable bulk density is required if proper feeding mechanism is not present (Zamora-Cristales et al. 2015).

- **Fuel form**

Biomass can be fed to gasifier in loose or densified manner. The form of fuel in which it is fed to gasifier has large impact on gasification process. In US densifying of biomass is practiced from last 40 years. All kinds of biomass can be densified into energy cube which are cubes or cylinders in shape. These cubes have a high density ranging between 600-1000 kg/m^3 .These cubes or pellets are easy to feed to gasifier and store as compared to raw biomass, hence small size hoppers can do the job (Bhavya et al. 2015).

- **Volatile matter content of fuel**

When temperature of fuel is raised the condensable and non condensable vapours are released. Quantity of vapours released depends at the temperature to which it is heated and rate of heating. In pyrolyis zone temperature is very high (about 150°C) which lead to liberation of inherent moisture and volatile matter present (Oanh et al. 2005). This leads to the formation of a vapor comprising of gases, water, oils and tar. Tar contents get increased with increase in volatile content in fuel which can cause problems for filter of IC engines. Variation in volatile matter of fuel leads to change in design of tar removal mechanism of gasifier. Crop residues have generally 63-80 %, volatile matter and wood has volatile content ranging between 72-78% (Xuan et al. 2009).

- **Ash content of fuel**

Mineral contents present in biomass material which cannot be oxidized are termed as ash. Small quantity of fuel which remains unburnt also contributes to ash part. Ash content and ash composition have impact on for smooth running of gasifier it is important to control the quantity of ash up to a certain limit. Clinker formation and slagging can take place in reactor if proper ash disposal techniques are not adopted. As a worst case clinkers and slagging can cause blocking of reactor zone or increase in tar content of gas. In general, below 5 % ash content is desirable for efficient working of gasifier. If ash content increases above 15%, it can cause severe problems. Woody materials have low ash content as compared to agricultural wastes. But cotton stalks also resemble to woody biomass in ash content (Capablo et al. 2009).

- **Reactivity of fuel**

The pace of reduction process of CO_2 into CO depends on the reactivity of fuel. Different fuels have different reactivity. Charcoal is most reactive preceded by wood. Reactivity depends on the number of active points on the surfaces of material. Stream treatment or treatment with sodium carbonate and lime can increase the reactivity of charcoal. Gasification process can be influenced by addition of various elements which act as catalyst such as addition of small quantities of Zink, sodium and potassium, can significantly increase reactivity of the fuel (Arias et al. 2008).

2.1.3 Advantages of use Biomass:

- **Renewable in nature**

Trimming of energy tree species like casurina, prosopis can provide near about 30 tonnes of biomass supply on a sustainable basis.

- **Cheap**

A large variety of agricultural wastes are available throughout the year at very low prices. The main cost is of transportation and storage. If gasification systems are equipped in remote villages, transportation and storage costs can be excluded and can provide energy at very low costs.

- **Clean fuel**

Biomass fuels are generally sulphur free. So they contribute to acid rain. IC engines run on producer gas generate lesser amounts of NO_x emissions. Also use of biomass does not cause green house effect as CO_2 emitted by use of agro wastes as fuel is fixed by next season crops. So on net basis no CO_2 is added to environment. On the other fossil fuels are generated in long times and hence CO_2 emitted by them remains in environment and causes green house effect.

- **Highly abundant**

A large amount of biomass fuel is generated every year. Due to its wide range biomass is easily available in almost all regions. Agricultural wastes, forest trims, municipal wastes and energy crops are some main sources. About 300 million ton of biomass is generated every year through agricultural wastes. This can meet 40% of primary energy needs if used efficiently.

- **Green in nature**

Increased demand of biomass will excite the cultivation of energy crops and will convert more free land into green which will help to increase green cover of planet.

2.1.4 Some limitations of biomass:

- Generally biomass materials have low bulk densities which make it costlier to handle, transport and store biomass fuels.
- Biomass fuels are not available in specific size range. Due to wide range of sizes pretreatment of fuels which increases cost.
- Gasifier design needs to be changed every time when we use different biomass fuels due to

difference in particle size, moisture content and variation in other properties.

- For efficient gasification, densification of low density fuels into suitably sized cubes or pellets is required which increase cost of power production.
- Biomass materials with high dirt and ash content are difficult and expensive to densify as they cause high die wear.

2.2 Gasification:

2.2.1 History:

Over 180 years ago organic fuels were started as feeds in blast furnaces to generate combustible gasses .After that it is realized that these gases can be used for power generation and heating applications. The first producer gas systems were emerged in Europe and they use peat and charcoal as fuel. After short period petroleum products achieved popularity as a fuel and after that no attention was put towards the development of gasification system (Molina et al. 1998). But during two world wars and particularly World War II, scarcity in the petroleum supplies causes tremendous increase in rates of petroleum products and this led to prevalent reintroduction and development of gasifier systems. Army vehicles, buses, trucks, agricultural machinery and industrial equipment were powered by gas by the year 1945 (Breag & Chittenden 1979). During this period, all over the world around 9000,000 vehicles were operated on producer gas. But after World War II availability of fossil fuels at low costs led to the lack of strategic momentum towards development gasifier systems (Moffat 1988).

This causes declination of producer gas industry in that era. In today’s scenario about 64 large gasification equipment manufacturers are playing their role in development of efficient gasification systems all over the world. An Indian based company named as Ankur Scientific Energy Technologies Pvt Ltd is licensed by BG Technologies of USA for worldwide distribution. Using this technology Ankur Scientific Energy Technologies Pvt Ltd has set up over 400 gasification units worldwide which generate producer gas by using palm nut shells, coconut shells, cotton stalks, maize cobs, soy husks, wood chips, rice husk and sawdust (Anon n.d.). The electric system of BG Technologies contains a biomass gasifier, gas cooling unit and cleaning systems and a diesel engine and generator set. In ideal conditions all the energy present in the biomass material can be converted into producer gas using gasification system. But in actual practice, 60% to 90% of energy present in the biomass materials can be converted into gas using gasifier systems.

2.2.2 Why Gasification?

Although a lot of alternative processes are available for biomass consumption, but process of gasification is best suited due to following reasons (McKendry 2002)

- Various biomass materials can be used as feedstock in the single system with little or no modifications.
- The efficiency of the gasification process is high due to thermo-chemical conversion. It generally ranges between 70% to 90%, which is higher as compared with other various available alternatives.
- In the high output ranges, technical considerations have little role in gasification output capacity. It is mainly dependent on proper treatment of raw biomass materials
- In the form of electricity or heat, gasification apparatus requires least are per unit energy generated as compared to other systems.
- As compared with steam turbine systems and biogas plants, gasification systems have the highest turn down ratios.

2.2.3 Methodology:

Generally biomass fuels are not available in a specific size range and excess of moisture content mainly the agricultural wastes which are freshly harvested. Due to a wide range of sizes and high moisture content the first step is the pretreatment of fuels to ensure the trouble free functioning of the gasifier. Agricultural wastes are generally dried using fresh air and sunlight. After this step air dried biomass is chopped or shredded into a definite size range generally varying between 4 to 25mm using various agricultural machinery available like cotton stalk shredder, threshers etc (Tinaut et al. 2008). This treated biomass material is put in biomass top hopper manually or using an automatic feeding system (in commercial use). After this biomass material moves to reactor where it burns in deficiency of oxygen to generate producer gas.

2.2.4 Ideal working parameters:

For efficient working of gasifier systems following conditions are required (Cummer & Brown 2002)

- Moisture content should be kept below 25% as it is difficult to ignite fuel with high moisture content and also higher moisture content causes reduction in the thermal efficiency of gasification process.

- Temperature of reactor of gasifier is kept between 900°C and 1100°C to obtain maximum calorific value of producer gas. If temperature is further raised above 1100°C process proceeds towards complete combustion which is not desirable.
- Particle size of biomass material is kept between 4mm to 25mm to avoid blockage chances and to obtain constant flow rates of producer gas.
- It is desirable to convert low bulk density biomass material into pellets or energy cubes if cost effective methods are available as they are easy to handle and feed.

Fig 4 Schematic diagram of gasifier system; 1 Biomass feeder 2 Feed door 3 Biomass hopper 4 Moist biomass 5 Drying & pyrolysis 6 Gasification 7 Air intake 8 Inner charcoal bed 9 Bed ash rotor 10 Fine ash collector 11 Cyclone separator 12 Wastewater collector 13 Passive sawdust filter 14 Fiber safety filter (Azam et al. 2008)

2.2.5 Chemical process of gasification:

The chemical process of gasification is defined by a series of chemical reactions of which, main

part is thermal decomposition of hydrocarbons obtained from biomass in an atmosphere which is reducing in nature or we can say in deficiency of oxygen. This process generally occurs at near about 900°C. Ash is prevented from melting by the injected air so in simple systems it is not always necessary to inject steam in gasifier. A gasifier generally operates at atmospheric pressure but it can run at elevated pressures if required. On the basis of heat source gasification process can be classified as direct system in which heat is generated by exothermic reactions using oxygen or air or indirect system in which heat is supplied to reactor from outside. The obtained gas contains a mixture of combustible gases (Di Blasi 2009). Main constituents of obtained gas are carbon monoxide (CO) and hydrogen. By-products obtained in the process are mineral matter (ash or slag), charcoal and liquids and tars. Air, oxygen-enriched air or oxygen (O2) is generally used as gasifying agent in the process. In case of high capacity gasifier systems which use fossil fuels, it is ideal to use Oxygen as oxidant but for biomass gasification air can be used as an oxidant. Complete chemical process of gasification is very complex. It is followed by sequence of a number of reactions (Karamarkovic & Karamarkovic 2010).
The complete chemical process can be described by the following reactions:

$$Biomass \xrightarrow{heat\ (300\text{–}400\ \circ\ C)} gases\ (CO, H_2, CO_2, light\ HC's) + char + pyrolysed\ \ vapors \tag{1}$$

$$Pyrolysed\ vapors \xrightarrow{(heat + high\ residence\ time)} gases\ (CO, CO_2, H_2, light\ HC's) \tag{2}$$

$$C + O_2 \longrightarrow CO_2 \qquad \Delta H = -393.5\ kJ/mol \tag{3}$$

$$C + (½)\ O_2 \longrightarrow CO \qquad \Delta H = -110.5\ kJ/mol \tag{4}$$

$$C + CO_2 \longrightarrow 2CO \qquad \Delta H = 172.4\ kJ/mol \tag{5}$$

$$C + H_2O \longrightarrow H_2 + CO \qquad \Delta H = 131.3\ kJ/mol \tag{6}$$

$$C + 2H_2 \longrightarrow CH_4 \qquad \Delta H = -74.8\ kJ/mol \tag{7}$$

$$CO + H_2O \longrightarrow H_2 + CO_2 \qquad \Delta H = 41\ kJ/mol \qquad (8)$$

$$CO + 2H_2 \longrightarrow CH_4 + H_2O \qquad \Delta H = 206\ kJ/mol. \qquad (9)$$

The partial oxidation (Eq. 4) reaction and char oxidation reaction (Eq. 3) are the slowest among all of the reactions described above and rate of overall gasification process is controlled by them. Most of the pyrolyzed liquids get cracked at higher temperatures but pyrolysis also gives a liquid which does not crack with increase in temperature. This liquid is called tar and proper cleaning set-up is required for removal of tar, which can increase cost in many cases. The complete gasification process can be broadly divided into the four subparts:

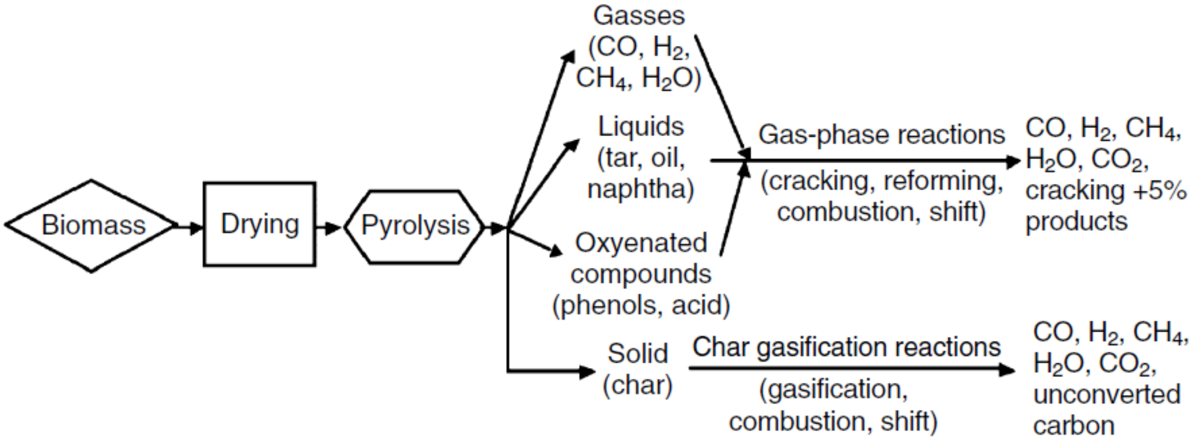

Fig5 Schematic diagram showing steps of gasification process (Rajvanshi 2014)**.**

- **Drying**

Generally biomass fuels are rich in moisture content which is not desirable. In most of cases moisture contents of agricultural wastes varies between 5% to 35%. For efficient processing biomass is first dried in drying zone by keeping biomass above 100°C. The water gets evaporated and is converted into steam. Biomass fuel does not experience any type of decomposition in drying zone (Rajvanshi 2014).

- **Pyrolysis**

In pyrolysis zone biomass fuel undergoes thermal decomposition in absence of oxygen. In pyrolysis zone three types of products i.e. gases, liquids and solids are released. Operating conditions and chemical composition of biomass material controls the ratio of products in this zone. The gas produced in this zone has low calorific value generally between 3.5 - 8.9 MJ/m^3. It is observed that during gasification process there is always a low temperature zone in which pyrolysis occurs, no matter how gasifier is built. Temperature in this zone is about 250°C. Main products of this zone are char and other volatiles like CO_2, CH_4, CO and C_nH_n (Roddy & Manson-Whitton 2012).

- **Oxidation**

Air is introduced in oxidation zone which contains water vapours, inert like argon, nitrogen etc along with Oxygen. These inert gases do not react with constituents of biomass fuel. The temperature of oxidation zone is high generally between 800°C to 1000°C. Carbon monoxide is produced by heterogeneous reaction between oxygen of air and solid carbonized part of biomass fuel.

$C + O_2 = CO_2 \qquad \Delta H = -393.5\ kJ/mol$ *(10)*

In this reaction 12 kg carbon is completely burnt with 22.39 m^3 of oxygen and 22.26 m^3 of CO_2 is liberated. Steam is produced by the reaction of Hydrogen present in fuel reacts with oxygen in the air blast (Higman & van der Burgt 2003).

$H_2 + ½ O_2 = H_2O \qquad \Delta H = 242\ kJ/mol$ *(11)*

- **Reduction**

There is absence of oxygen in reduction zone and many reactions take place in this zone at high temperature. Main reactions occurring in reduction zone are stated below (Yang 2004).

- Boudouard reaction

$CO_2 + C = 2CO \qquad \Delta H = 172.4\ kJ/mol$ *(12)*

- Water-gas reaction

$C + H_2O = CO + H_2 \qquad \Delta H = 131.3 kJ/mol$ *(13)*

- Water shift reaction

$CO_2 + H_2 = CO + H_2O \qquad \Delta H = 41.2 kJ/mol$ *(14)*

- Methane production reaction

$C + 2H_2 = CH_4 \qquad \Delta H = -74.8\ kJ/mol$

In reduction zone heat is required for the reactions to occur. This causes decrement in the gas temperature. All the carbon present in biomass gets reduced to carbon monoxide or get combusted, if complete gasification takes place. A mixture of combustible gases is also yielded along with carbon monoxide and other mineral matter gets vaporized in the process. Some char (unburned carbon) and ash are left behind (Pereira et al. 2012).

2.2.6 Products of gasification:

- **Producer gas:**

Producer gas is the main and desired component of gasification process. CO; CH_4, H_2; N_2; and CO_2 are the main components of producer gas. Ratios of these gases are influenced by the type of biomass. Percentage of CO and H_2 is generally 30-35% by volume in air blown gasification. N_2, CO_2 and CH_4 are present in ratios 50-55%, 15-17% and 3-5% by volume respectively.

- **Tar:**

Tar is the undesirable by-product of gasification process. It consists of condensed black colored viscous aromatic compounds such as benzene and its derivatives. It also contains some resins and alcohols.

- **Ash:**

Another undesirable product of gasification process is ash. In combustion processes ash is not desirable. Since biomass fuels have low quantities of ash, little amounts of ash are produced in gasification process. Proper ash removal mechanisms are provided in gasifiers which remove ash after short intervals.

2.3 Gasifier:

Gasifiers have quite simple operating mechanisms. Gas cleanup and feeding operations of gasifiers are not complicated. But is not as simple to successful operate the gasifiers because of absence of neat rules of operation. This is due to fact that is not easy to understand the thermodynamics of gasifier operation. Air supply, temperature and other operating parameters of the gasifier reactors are yet determined by nontrivial principles of thermodynamics (Jang et al. 2002). The various factors such as type of fuel used nature of gasifier whether mobile or stationary influence the design of gasifiers. Generally gasifiers are classified on the basis of source of heat supply to reactor and direction of movement of air blast and biomass in the reactor of gasifier. On the basis of above stated parameters several designs of gasifiers exist

(Ng et al. 2013; Capareda et al. 2007; Usón et al. 2004). Main classes of gasifiers are:

- Fixed Bed Gasifiers
- Fluidized bed gasifiers

Fixed bed gasifiers are further classified as up draft gasifiers and down draft gasifiers and Fluidized bed gasifiers have subclasses known as circulating bed gasifiers and bubbling bed gasifiers.

The most commonly used gasifier types are stated in table1.

Table 1 Classification of gasifiers

TYPE OF GASIFIER	**FLOW DIRECTION**		**Heat source**
	FUEL	**OXIDANT**	
Down-Draft	Down	Down	Partial combustion of volatiles
Up-Draft	Down	Up	Char Combustion
Circulating fluidized bed	Up	Up	Combustion of volatile matter and char
Bubbling fluidized bed	Up	Up	Combustion of volatile matter and char

- **Fixed-bed gasifiers**

In fixed bed gasifiers biomass is fed top of the gasifier reactor and a bed is formed. When air passes through this bed, it gets gasified. Ash and char formed when material releases volatile components in process exit through the grate present at bottom of gasifier. In fixed bed gasifiers, generally temperatures vary from 750° to 950°C. Fixed bed gasifiers are further classified as updraft gasifier and downdraft gasifier. Updraft gasifiers are also known as counter flow gasifiers. These are the oldest and Simplest and oldest type of gasifiers is updraft gasifiers which are also called counter flow type gasifiers.

- **Updraft gasifier**

In case of updraft gasifiers zones of partial combustion, pyrolysis and reduction are clearly defined. Air enters the gasifier from the bottom of reactor and flow countercurrent to the direction of fuel flow. The outlet of producer gas is relatively at higher location in case of updraft gasifier which helps in achieving higher efficiency because while passing through fuel bed gasses lose their heat and leave gasifier at relatively lower temperatures. Fuel is preheated and dried with the sensible heat given by gasses while passing through fuel bed. In updraft gasifier biomass fuel is fed from the top of the reactor and reacting bed is supported by a grate present at the bottom of the gasifier (Pedroso et al. 2013).

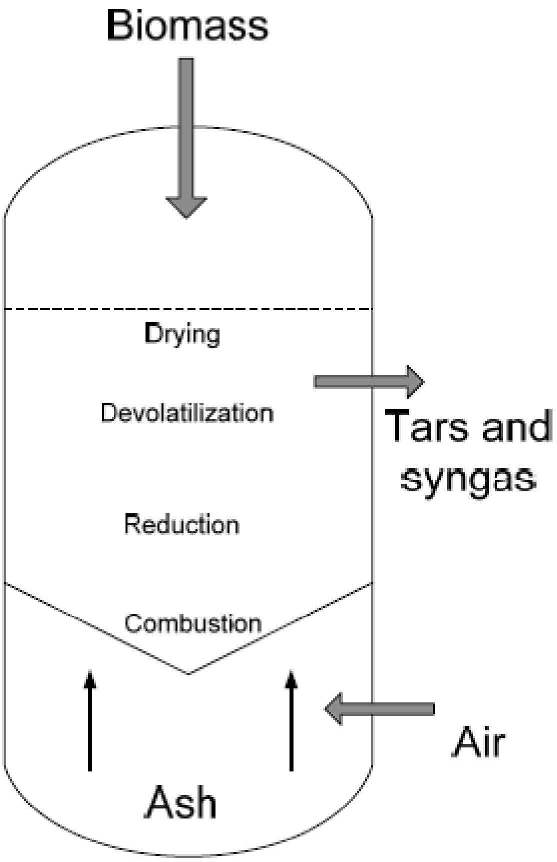

Fig 5 Schematic diagram of fixed bed updraft gasifier. (Saravanan and Nagarajan 2010)

Carbon dioxide (CO_2) and water (H_2O) are liberated at the bottom of gasifier bed by complete combustion of char. The hot gases having temperature near about 1000°C move upwards the gasifier bed above, where they get reduced into carbon monoxide (CO) and hydrogen (H_2) and consequently their temperature decreases to 750°C. While further upward movement of reducing gases (H_2 and CO) in the gasifier, the descending dry biomass is pyrolysed and at last incoming wet biomass fuel is dried by them. Gases leave gasifier at a low temperature near about 500°C.

The major advantages of updraft gasification are:

- Design of these type of gasifiers is quite simple
- There manufacturing and operating cost is low.
- This type of gasifiers are capable of handling high moisture content biomass fuel.

Major disadvantages of updraft gasifiers are that producer gas generated by these types of gasifiers contains large amount of tar and also loading capability of these gasifiers are poor (Saravanan & Nagarajan 2008).

- **Downdraft gasifier**

Downdraft gasifier is also called cocurrent-flow gasifier. The mechanical configuration of downdraft gasifier is same as that of updraft gasifier. The only difference is that produced gases and oxidant flow in same direction of movement of biomass. In case of downdraft gasifier 99.9% tars produced in process can be combusted. Reaction zone is located at the top of the reactor where biomass fuel having low moisture content and oxygen or air are ignited. Pyrolyzed vapours are generated by flame which burns extremely leaving hot combustion gases and 5 to 15% char. More CO and H_2 are formed by the reaction of combustion gases and char at a temperature range of 800-1200°C. Ash and unconverted char are passed to the bottom of gasifier grate and are sent to the disposal. The problem of high tar content in gas in updraft gasifier is minimized in case of downdraft gasifier which helps in smooth function of IC engines on produces gas.

In downdraft gasifier gas is drawn from the bottom. In downdraft gasifiers time taken to ignite the fuel and bring the process to working temperature range is short (20-30 minutes) as compared with the updraft gas producer.

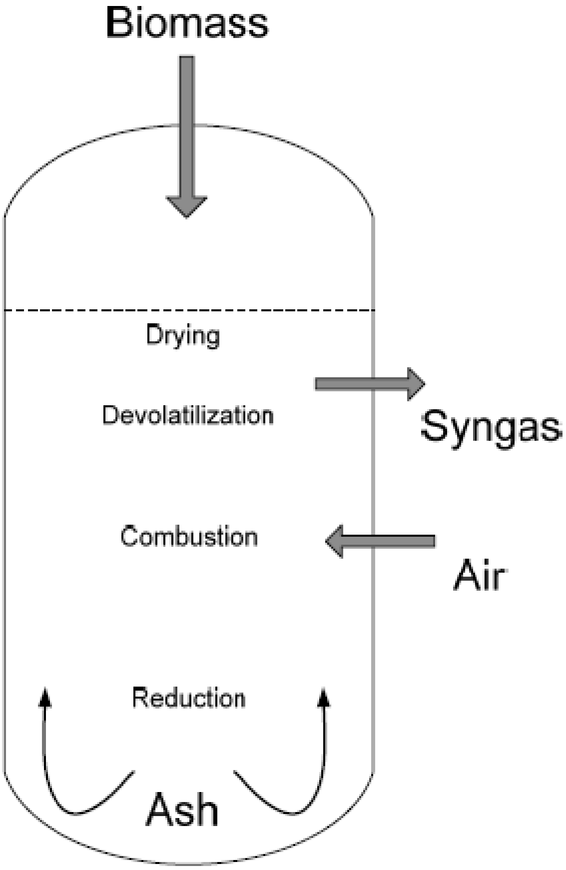

Fig 6 Schematic diagram of fixed-bed downdraft gasifier (Saravanan & Nagarajan 2010)

Advantages of down draft gasifiers are:

- Clean producer gas output with low tar ratio.
- No tar cleanup required as 99.9% tar produced is consumed in the process.
- Cyclone washers are not required as most of the minerals remain with ash.

Major disadvantages of downdraft gasifiers are:

- Overall efficiency of process is low.
- Biomass with high moisture content is difficult to process in downdraft gasifiers.
- Gas temperature is high at outlet so proper cooling mechanism is required.

- **Twin-fire Gasifier**

Twin fire gasifiers have two reaction zones. In the upper reaction zone, processes like drying and low-temperature carbonization cracking of gases take place. While lower zone is responsible for permanent gasification. Temperature range of process is 460 to 520^{O}C. Twin-fire gasifiers are capable of generating fairly clean producer gas (Kramreiter et al. 2008).

- **Crossdraft gas producer**

In case of crossdraft gasifiers ash bin, fire and reduction zone are divided. Due to this type of design, only fuels having low ash content like coke, wood, charcoal etc can be used in crossdraft gasifiers. Operating temperatures of these type of gasifiers is quite high (2000°C). When operated on dry fuel, producer gas obtained from crossdraft gasifiers has high CO concentration and low H_2 and CH_4 (methane) content in it due to higher temperature in reactor. Start up times of Crossdraft gasifiers is quite short (5-10min) as compared with updraft and downdraft gasifiers. Even though Crossdraft gasifiers have some advantages over downdraft and updraft gasifiers, they are not ideal for use. The major draw backs like high velocity and temperature of producer gas at outlet and poor CO_2 reducing capabilities make them inefficient for common use (Visagie 2008).

- **Fluidized bed gasifiers**

A fixed bed gasifier can be converted into fluidized bed gasifier by increasing the volumetric flow of gas through the grate. Oxidizing gas fluidizes the inert bed material by creating turbulence in it. High heat and mass transfer is created by mixing of hot inert material and biomass entering from above of top of bed. Fluidized systems operate at same temperature ranges as that of fixed bed gasifiers. Major advantages of these gasifiers include their capability of high volumetric flows, uniform temperature distribution and more flexible feeding. The fluidized-bed gasifiers are subdivided into bubbling fluidized bed gasifiers and circulating fluidized bed gasifiers (Van Den Enden & Lora 2004).

- **Bubbling fluidized bed gasifier**

Bed of this type of gasifier contains fine inert particles of alumina or sand. These particles are selected on the basis of their thermal properties, size and density. A state can be achieved where weight of solids is counterbalanced by frictional force between the gas and particles by forcing oxygen or air through inert particles.

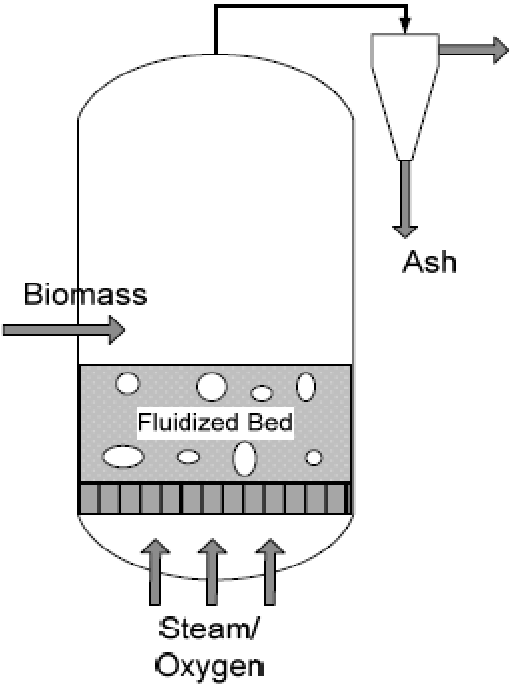

Fig 7 Schematic diagram showing bubbling fluidized bed gasifier (Saravanan & Nagarajan 2010)

The inert particles remain in the reactor of gasifier and emerge to be in a boiling state by blowing gas at fluidization velocity through the bed which causes bubbling and channeling of gas through inert particle media. Biomass fed to reactor is broken by the fluidized particles which help in good heat transfer throughout the reactor of gasifier.

The main advantages of bubbling fluidized bed gasifier are:

- Uniform producer gas is yielded in process.
- Temperature distribution in reactor remains uniform.
- Wide range of particle sizes can be processed in these gasifiers.
- Heat Transfer rate between gas, fuel and inert material used is high.
- Quantities of tar and unconverted carbon are less.

The main drawback of bubbling fluidized bed gasifier is that sometimes formation of large sized bubble can lead to gas bypass through the gasifier bed (Kaushal et al. 2010).

- **Circulating fluidized bed gasifier**

Operating gas velocities in case of fluidized bed gasifier are greater than minimum fluidization velocity, which leads to entrainment of inert particles in the gas stream. Entrained inert particles in the gas stream come out of reactor from the top of gasifier and they are separated with the help of a cyclone separator and are resent to the gasifier reactor.

The main advantages of circulating fluidized bed gasifiers are:

- Circulating fluidized bed gasifiers are suitable for rapid reactions.
- High heat capacity of bed material helps in high heat transport rate.
- Unconverted carbon and tar quantities are less in process.

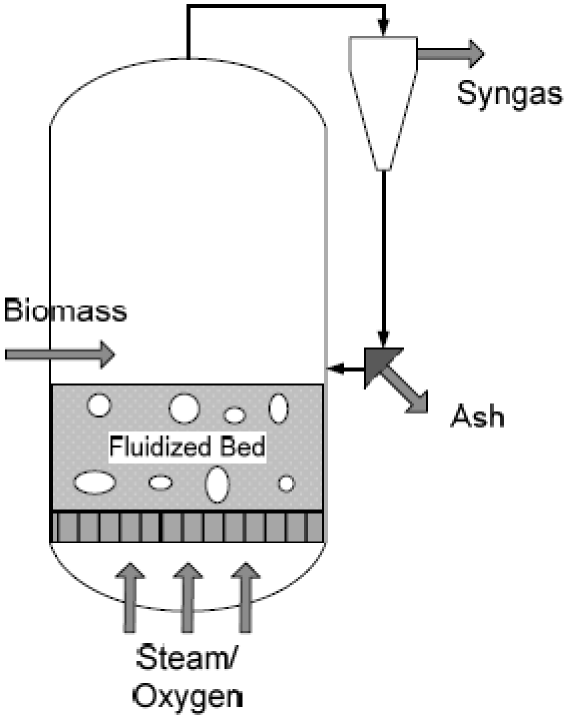

Fig 8 Schematic diagram of circulating fluidized bed gasifier (Saravanan & Nagarajan 2010)

The main drawbacks of circulating fluidized bed gasifier is that the minimum transport velocity of fuel particles is determined by their size and if gasifier is operated at high velocities equipment erosion can take place (Ju et al. 2010).

- **Entrained flow gasifiers**

One more commonly used gasifier is entrained flow gasifier. Entrained flow gasifiers are operated at high pressures generally up to 50 bar. Only very fine fuel particles are used for gasification process and operating temperatures are kept high, so that complete gasification can take place in short residence times in gasifier. This type of gasifier is investigated by energy research centre of Netherlands and they have reported promising performance with pretreated biomass. It id tried to time of residence of particles equal to the approximate time required for a particle to cover the length of reactor of gasifier. For this purpose particle sizes are kept small generally less than 1mm. For efficient gasification it is recommended to keep temperatures high generally in rage of 1100°C to 1500°C. In entrained flow gasifier fuel is mixed with stream of steam or oxygen in order to maintain a turbulent flow in the gasifier. On the inside wall of reactor, a liquid slag is formed by the melting of ash forming components which helps effectively in protecting the wall. Limestone is added in gasifier as a fluxing material to form slag. The sufficient natural fluxing material is present in materials which are rich in alkali content such as herbaceous biomass (corn stover or switchgrass).

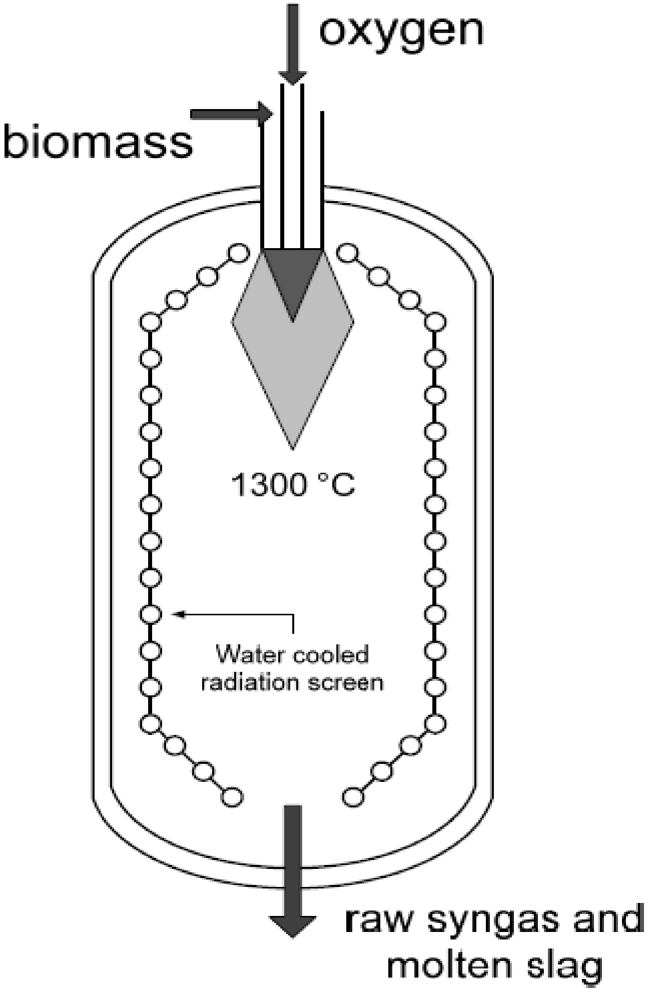

Fig 9 Schematic diagram of entrained flow gasifier (Saravanan & Nagarajan 2010)

The main advantages of entrained-flow gasifiers include:

- Due to complete char gasification, methane and tar contents in gas are negligible.

- High carbon conversion rates.
- Producer gas cleaning is simplified as there is no need to use cyclones for tar removal.

The major disadvantages are that the operation is complex and it is difficult to maintain high temperatures throughout the process (Watanabe & Otaka 2006).

2.4 Dual fuel engines

Internal combustion engines operating on gaseous fuel have for long been known .Many large stationary engines use two fuels. Generally out of two fuels, one is liquid and the other is in gaseous form. Widely varying proportions of two fuels can be taken to run the engine and such engine is called a dual fuel engine. The earliest diesel engine which was patented by Dr. Diesel was essentially a dual fuel engine. It was operated on gaseous fuel ignited by oil injection in the combustion chamber. It is only after the world war I attention was focused on the dual fuel engines due to scarcity of liquid fuel and the awareness about the availability of gaseous fuels at cheaper rates as compared with liquid fuels. The development of very large tankers capable of transporting liquefied gases economically has made natural gas available to most parts of the world at rates cheaper than the liquid fuels (Abd Alla et al. 2000). The gaseous fuels require a high compression ratio to burn efficiently because they have high self ignition temperature. Natural gas is composed of mainly (about 95%) methane and other light paraffin that have self ignition temperature of about compared to 470^{o}C of octane. For this reason, mainly diesel engines have been used as dual fuel engines. Moreover, a diesel engine has an ability to run over a wide range of fuels ranging from light fuels like JP-4 and kerosene to heavier fuels and crude oils. These type of engines are beneficial in power generation. The possibility of operating a diesel engine on liquid fuels such as gas oil or diesel oil and on gaseous fuels such as producer gas, coke gas, sewage gas and natural gas etc is combined in a simple way by dual fuel operation. The engine can be switched from dual fuel to diesel operation immediately in emergency condition (Cummins Engines Ltd.).

2.4.1Working Principle:

The dual fuel engines operate on diesel cycle. As suggested by name there are two fuels used primary fuel and secondary fuel. Primary fuel is generally gaseous in nature and secondary fuel which is also called pilot fuel is liquid in nature. There are two common ways for supplying gaseous fuel. In first method primary fuel is supplied by using supercharger at a higher pressure than atmosphere pressure. In other method primary fuel (gaseous fuel) is directly added to the air intake manifold and is sucked by the engine. Compression of gaseous fuel and air mixture takes place similarly as in normal diesel engine operation. Using conventional diesel engine fuel supply system a small quantity of pilot fuel (liquid fuel) is added in the compression stroke, at some point near TDC (top dead centre). Injection of pilot fuel helps in proper ignition. Many flame fronts are established by ignition of air gas mixture at number of places. It is desirable in process as it helps in rapid and smooth starting of combustion process (Abd Alla et al. 2000).

The propagation of combustion by flame fronts in dual fuel engines is similar to that in case of spark ignition engines but starting of combustion process resembles with compression ignition engines. The control of power output is done by varying supply of gaseous fuel (primary fuel) to the inlet manifold of engine. The amount of liquid fuel (pilot fuel) varies from 5% to 7% and usually it is kept for a particular engine. Dual fuel engines can be run on either diesel oil, gas or on mixture of two fuels. The working range of temperature ratios of these engines is quite wide (Lee & Ryu 2005).

2.4.2 Factors affecting combustion in dual fuel engines:

A large number of factors which affect the combustion process in dual fuel engines. Among them the important one's are:

- **Quantity of pilot fuel**

Ignition in dual fuel engines occurs in an envelope which encloses the spray of secondary fuel (pilot spray) and after this, it gets propagated to the rest of the charge. The secondary fuel (pilot fuel) undergoes pre combustion reactions and releases thermal energy which increases the temperature of the gaseous fuel and a flame front is developed. If the amount of pilot fuel is increased more energy will be available for primary fuel (gaseous fuel) and the combustion would be very rapid which results in an increase of maximum pressure rise rate. Therefore a large quantity of pilot fuel will result in knocking because of very rapid rates of pressure rise (Liu et al. 2013).

- **Injection timing**

Normal injection timing is within 20° to 16° BDC. Advancing the injection timing results in increase in maximum cylinder pressure and knocking occurs at a leaner mixture. Retarding the injection timing reduces the delay of ignition but despite of reduction in ignition delay the combustion starts only after TDC. This reduces the maximum pressure rise rate and also the efficiency of dual fuel engine as part of the expansion stroke is lost without giving any useful power output. However the overall effect of the injection timing is not very high except that at a slightly retarded timing there is some improvement in the efficiency but pressure rise rate also increases which makes engine more near to knocking condition (Nwafor et al. 2000).

- **Effect of cetane number of pilot fuel**

It is an important factor. With increase in the cetane number of secondary fuel (pilot fuel) the rate of pressure rise near the knock limit is slightly reduced. Thus a slight increase in the mixture strength is allowed near the knock limit. However, the power output is not improved. The use of low cetane number fuels results in poor performance of the engine and greatly affects the combustion. In general the ignition quality of the secondary fuel has small effect on the combustion in a dual fuel engine as compared to the ignition quality of the primary fuel (Kidoguchi et al. 2000).

- **Effect of type of gaseous fuels**

The power output of dual fuel engines which is limited by knock is greatly dependent on the type of primary fuel (gaseous fuel) used. As already stated the power of dual fuel engines varies logarithmically with the inverse of absolute inlet temperature of all hydrocarbon fuels but varies linearly with inlet temperature when hydrogen is the fuel. Methane which is a main constituent of natural gas does not undergo decomposition during the compressions in the engine and is more resistant to knock, pre ignition and backfiring from cylinder into gas/air inlet than other gases such as town gas etc. The main effect of the type of fuel is on the ignition and knocks limits. Due to wide variation in the composition of various types of gaseous fuels available all over the world it is not possible to give their effect on performance of dual fuel engine (Park et al. 2011).

- **Effect of throttling**

It is usual for conventional SI engine to resort to throttling for richer mixtures and improve the part load efficiency. However, when throttling is used on a dual fuel unit maximum cylinder pressure reduces greatly. This is because in throttled dual fuel engines ignition takes place very late in the cycle because of ignition delay. Thus combustion occurs after TDC and as a result maximum cylinder pressure gets reduced. The amount of throttling before the ignition failure limits are reached is very low. A diesel engine can run up to 50 percent throttling while decrease of 0.05bar in the inlet pressure might cause ignition failure due to increased ignition delay in dual fuel engines (Mayer et al. 2003).

- **Effect of mixture strength**

The mixture strength is the charge of dual fuel engines is strongly dependent on the amount of pilot fuel injected in the combustion chamber.

2.4.3 Control of knock in dual fuel engines

The dual fuel engine output is limited by knock, thermal and mechanical loading. Of these knock is the most important. Knock in dual fuel engines can be controlled by any of the following methods:

- Excess supply of air
- Use of cold combustion air
- Increased cooling of piston
- Use of additives
- Reducing the pressure of the gaseous

All these methods tend to reduce the reaction rates and hence limit the maximum pressure rise rate in the engine cylinder. Tetra methyl lead has been used to control knocking in the dual fuel engines. When a gaseous fuel contains a large proportion of gases liable to promote knocking it should be used on mixed-fuel principle.

2.4.4 Advantages of dual fuel engines

In addition to inherent advantage of using efficiently the cheap gas available from various sources the dual fuel engine has substantial advantage over a diesel engine which are listed below:

- In case of dual fuel engines exhaust is clean as gaseous fuel burns without leaving any residue. This helps in prevention of air pollution.
- The clean combustion results in reduced wear of the engine parts and reduced combustion of

the lubricating oil. The lubricating oil changes periods are also increased as the maximum pressure in the cylinder are less than those for a diesel engine, thereby reducing the blow by past piston. This reduces the contamination of the lubricating oil.

- The utility of power plant is highly increased by its ability of immediate change over from diesel oil to gaseous fuel and vice-versa. Continuity of service can be assured if due to some reason the gas supply breaks down
- Quantity of liquid fuel required to run engine is small.
- Dual fuel engine is very suitable for total energy installation. For example, the exhaust heat of the engine can be used for digesting the sludge in a sewage disposal plant and the sewage gas produced can be used to run the engine itself.
- A typical use of dual fuel engines is to produce synthetic gas, which is a mixture of CO and H_2, by burning methane in it and also producing power at the same time.
- For LPG tankers, these engines are ideally suitable as they can utilize the gas which evaporates during transportation, by suitably arresting it.

2.5 Review of Previous Research work

Perez et al 2012 carried out experiments by varying particle size and moisture content of pine bark on fixed bed downdraft reactor to obtain optimal gasification conditions. Pine bark is used as raw material for experiment.

Optimal conditions are reported as follows:

- Optimum superficial velocity of air is reported as 0.06 m/s.
- Range of particle size of biomass for proper working is between 2 mm and 6 mm.
- Moisture content of biomass fuel is kept below 10%.

The results obtained by maintaining above optimal conditions are:

- Biomass consumption rate = 125 kg/h/m^2,
- LHV of the producer gas = 2965.6 kJ/N m^3

Producer gas obtained from process maintaining optimal conditions has composition as 13.0% CO, 1.4% CH_4, 8.0% H_2, 14.9% of CO_2, and 62.7% of N_2.

Koroneos et al 2011 predicted the composition of the producer gas from cotton stalks by varying moisture from 0 to 30%. It is shown that increase in moisture content of biomass particles is not desirable for gasification process.

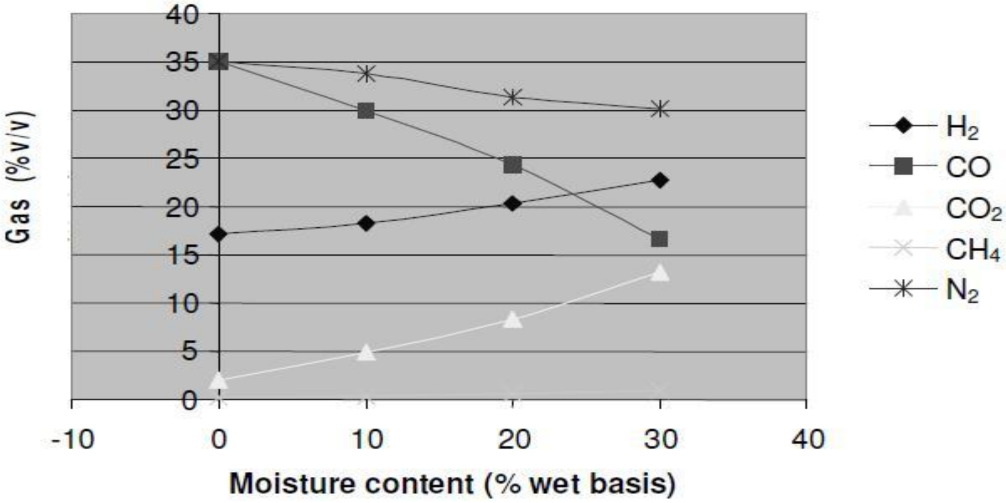

Fig 10 Effect of moisture content in the cotton stalks on gas composition (Koroneos et al 2011)

With increase in moisture content decrease in CO content in producer gas is observed whereas H2 and CH4 content increases. Beyond 20% moisture, CO content decrease rapidly to 15%.

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.

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 fiber 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.

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% CO_2, 15-20% H_2, 0.5-2% of CH_4, and rest is O_2, N_2 and CxHy.

Hanaoka et al. 2005 used a fixed bed downdraft gasifier to study effect of variation in components (cellulose, lignin etc) of woody biomass on the process of gasification. Air stream is used as gasifying agent and temperature range is kept about 1170K.

Main observations are as follow:

- It is noted that carbon conversion rates in lignin, cellulose and xylem were 52%, 97% and 92% respectively.
- In case of gasification of cellulose producer gas composition was 28:7 mol% of H_2, 27:0 mol% of CO_2 and 35:5 mol% of CO.
- In case of cellulose gasification composition of CO was greater than compositions of H_2 and CO_2. This trend resembles gasification of Japanese Oak, which has cellulose as main component.
- Producer gas composition obtained from lignin and xylem was 32 mol% of H_2, 36 mol% of CO_2 and 25 mol% of CO.
- In this case compositions of H_2 and CO_2 are greater than composition of CO. This trend resembles gasification of Japanese red pine bark, whose main component is lignin.

In air stream gasification composition of producer gas obtained from different woody biomass materials can be predicted by using information provided gasification of each component of woody materials separately.

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. The various parameters evaluated in the study are composition of producer gas, CV 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 producer gas decrease with increase in equivalence ratio till value of 0.205.
- If value of equivalence ratio is further increased from 0.205, fractions of CO_2 and N_2 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 at0 $\boldsymbol{\varphi} = 0.205$.
- Calorific value is maximum 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.

Sivakumar et al 2010 performed experiments using a downdraft gasifier. Three biomass materials are used for gasification process 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:

- The producer gas obtained from coconut shells has 23% higher calorific value than producer gas obtained from groundnut shells and 45% higher than gas obtained from rice husk
- Producer gas generated from coconut shells contains 17% and 21% higher amounts of CO as compared with ground nut shell and rice husk respectively.
- Ratio of hydrogen in gas is highest in case ground nut shells.
- In case of gasification of coconut shells methane content in gas is 6.1% and 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.

Jorapur et al 1997 developed a gasification system for thermal applications on commercial scale which is able to produce 1080 MJ/h. It uses low density biomass material such as sweet sorghum stalks, bajra stalks and sugarcane leaves and bagasse as fuel. Investigation shows that gasifier systems running on low density biomass material can meet the thermal needs successfully at low costs. It is found that sugarcane leaves and bagasse are best suited fuel for gasifier used for thermal applications as they are available at low costs approximately Rs 1350/T. This system is capable of replacing conventional boilers and furnaces run on fossil fuels which are used in metallurgical industries on large scale.

Sahoo et al. 2009 conducted a number of experiments to evaluate performance and emission characteristics of conventional diesel engine by running it on dual 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 H_2 and CO are used to study influence on various engine emissions (HC, NOx and CO) and performance parameters such as thermal efficiency, maximum cylinder pressure, exhaust gas temperature and diesel substitution). The diesel 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%, 100%) and ratios of H_2 and CO in gas used for study are 50:50, 75:25 and 100:0.

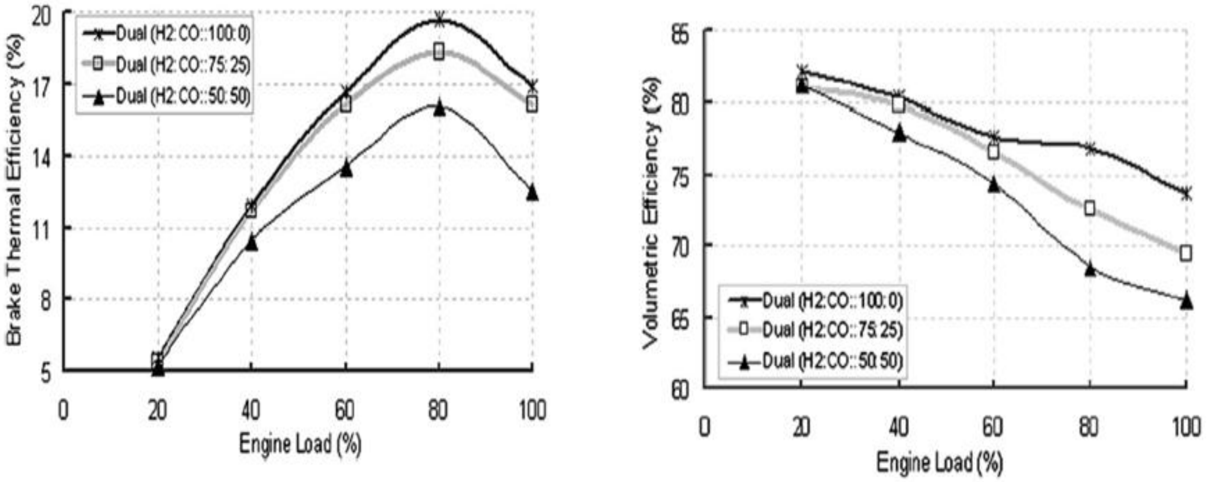

Fig 11 Effect of load variation on thermal efficiency and volumetric efficiency at different ratios of CO and H_2. (Sahoo et al. 2009)

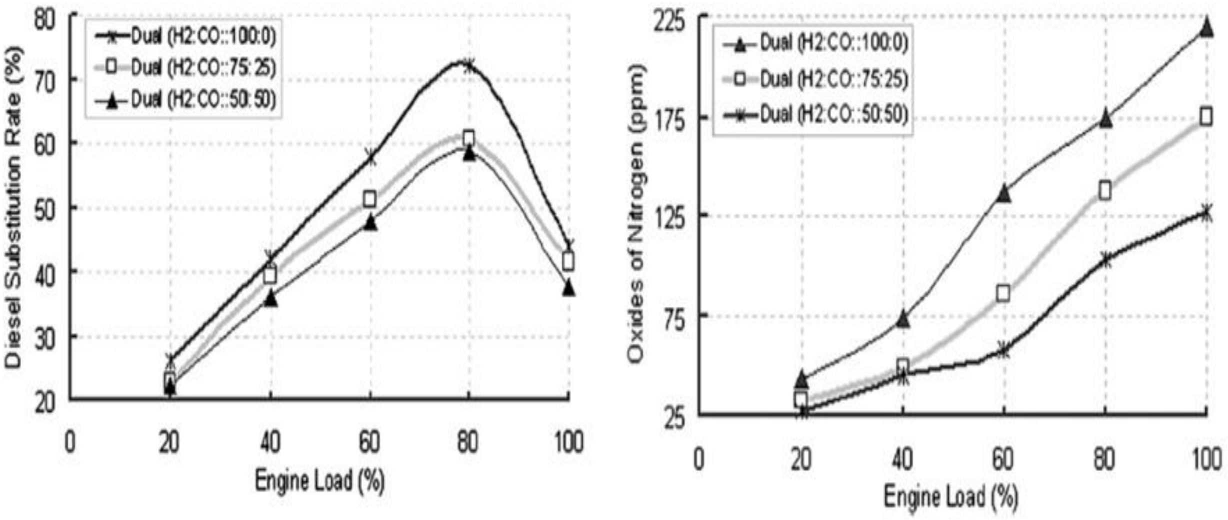

Fig 12 Variation in diesel substitution and amount of NOx emissions at different loads. (Sahoo et al. 2009)

In this way, the influence of syngas fuels obtained from various sources and processing methods can be examined using this study.

(Vyas & Singh 2007) examined the feasibility of gasification of Jatropha seed husk using a down draft gasifier of open core type. The various fuel properties of husk are also tested. Performance of process is represented in terms such as efficiency of gasification, calorific value of gas produced and consumption rate of fuel.

Main conclusions of study are:

- Increase in flow rate of gas leads in increase in calorific value of producer gas.
- Efficiency of gasification process and CO concentration also show an increase with increase in gas flow rate.
- The maximum value of efficiency of gasification is 68.31% and it is achieved at a gas flow rate of 5.5 m^3/h.
- The achieved rate of gasification in process is 270 kg/ m^2 h which is similar to that of gasification of hard wood.

Tripathi et al. 1998 availability of various agricultural residues in different seasons and at different geographical locations. Eight agricultural residues are considered in study. Assessment of various agricultural residues such as groundnut shells, rice husk, cotton stalk, maize stalk, mesta and jute sticks, arhar stalk and maize cobs is done. It is observed net availability of these residues is about eight million tones every year and they have potential of producing 1200 Peta Joules. Net cost of biomass material is estimated by cost of agricultural residue and the distance of transporting. Generally net cost of availability varies between Rs 132/tonne to Rs 628/tonne which is very low as compared with cost of coal in India. It is concluded that use of these agricultural residues in briquetting plants and power production by gasification technology is highly beneficial.

Chen et al. 2008 noticed that engine's brake specific fuel consumption increases with increase in oxygen content of fuel blend. It is also observed that NOx emissions are slightly increased with increase in oxygen content of fuel and on the other hand particulate matter and smoke are reduced.

Sridhar et al. 2001 conducted experiments on diesel engine using blends of diesel-producer gas and rubber seed oil-producer gas to find difference in carbon monoxide emissions in two cases. It is found that at all loads, amount of CO emissions is higher in case of rubber seed oil-producer gas blend as compared with diesel-producer gas operation. This reason behind this variation is the low calorific value of latter fuel which leads to more fuel consumption. Carbon dioxide emissions are also higher when blend of rubber oil-producer gas is used to operate the system. Other exhaust emissions are found to be nearly same in each case.

Uma et al. 2004 studied emission characteristics of dual fuel engines at various load conditions. It was found that emissions of dual fuel engine were generally low and are acceptable by emission norms when engine is operated at optimum load i.e. at 80% of the total rated load. But the carbon monoxide emissions were higher in case of dual fuel mode operation as compared with normal diesel operation.

The main factors which cause increase in CO emissions are:

- Producer gas used has low calorific value as compared with conventional fuels.
- Adiabatic flame temperatures of gas are low.
- Mean effective pressures of dual fuel mode operation are also less.

Although in dual fuel mode CO emissions are more at all loads than in normal diesel operation but a noticeable decrease in Sox and NOx emissions is noticed which is a positive sign.

Rajvanshi & Joshi 1989 have done an analysis by using a topless gasifier run on gasifier. Gas produced from gasifier is used for a very different purpose. It is coupled with a 3.75 KW diesel engine and engine torque is used to operate a pump set for pumping water. It is noticed that with consumption of 125 ml of diesel and 1.3kg of wood, 1 kWh energy can be produced. The system runs smoothly without any problems and is economical in use. It is concluded that with diesel substitution of about 60% which is easy to achieve, cost of water pumping can be reduced considerably. This set up can be used in remote areas for water pumping operations where electricity is not available.

Rao et al. 2010 used a modified dual fuel stroke diesel engine which has single cylinder. Intake side of diesel engine is incorporated with a LPG carburetor and alterations are done with fuel injection system to introduce only pilot fuel in cylinder. A computer is connected to engine for storage and analysis of data and to generate data on-line. Engine is run on different LPG proportions and at different loads. Engine is kept at a constant speed of 1500 rpm.

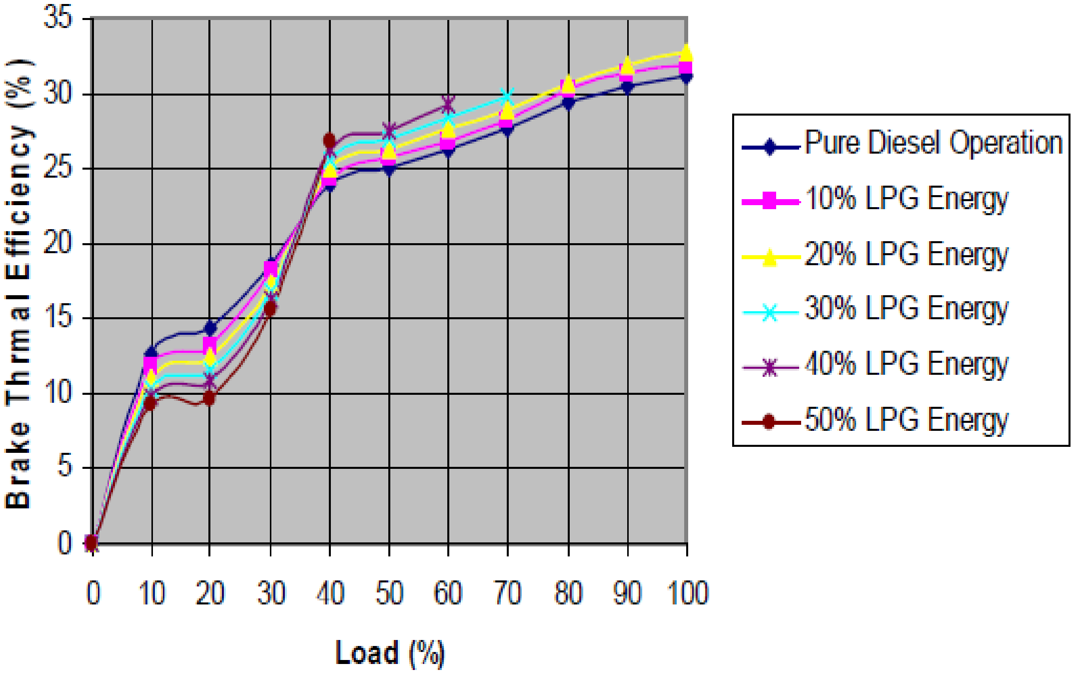

Fig 13 Variation in brake thermal efficiency with change in load (Rao et al. 2010)

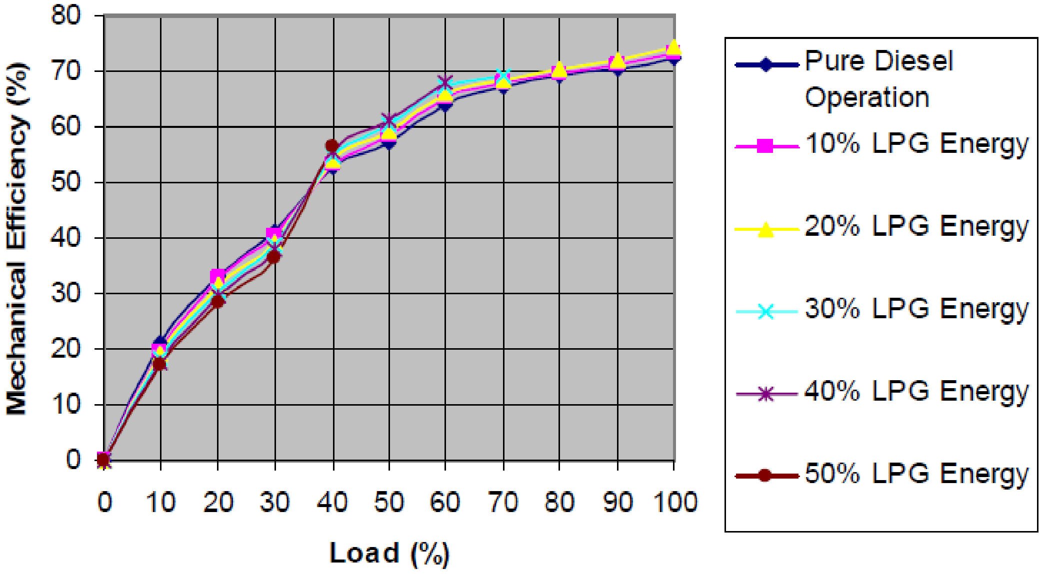

Fig 14 Mechanical efficiency at different loads. (Rao et al. 2010)

According to this analysis, approximately 50% substitution of LPG energy is possible at lower loads but at lower loads LPG substitution is limited to 20% only. At lower loads performance is better in case of only diesel mode but at higher loads engine performance is superior in dual fuel mode. This trend is also seen in emissions also. Considerable reduction in noticed in smoke density in dual-fuel operation. It is concluded that engine should be operated at diesel only at lower loads to obtain satisfactory performance and subsequently for higher loads, Dual fuel mode should be used for better performance. Threshold load of transition at which system should be switched from diesel only mode to the dual fuel mode is about 35% of total rated load. At higher loads it is convenient to use dual fuel engines in a number of applications for achieving satisfactory performance.

Saravanan & Nagarajan 2010 found that in case of hydrogen operation maximum brake thermal efficiency obtained at full load is 25% which is higher than case of pure diesel operation. In pure diesel operation maximum efficiency noted is 23%. At 75% load, in case of hydrogen operation amount of NOx emissions generated is 20.26 g/kWh which is higher than diesel operation which is 17.92 g/kWh. For improving performance use of hydrogen as fuel in dual fuel mode is highly accepted in history. Either electronic or mechanical injectors can be used for injection of hydrogen. Use of electronic injectors offer greater command on injection duration and injection timing. It also offers quick response which is highly desirable for high speed operations of engine. It is reported that hydrogen should be injected directly to the intake manifold to attain precise control on hydrogen flow and it also helps in avoiding pre ignition problems. If direction injection fuel system is used, the major problems linked with injection of hydrogen in inlet manifold like deaerating of power, back fire do not occur. The only major drawback seen in use of hydrogen as fuel in dual fuel mode is increase in NOx emissions.

Sheng & Azevedo 2005 report importance of heating value of biomass fuels in designing and simulations tasks of biomass thermal conversions systems. Analysis of various methods available in 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 literature. It is reported that correlations done on the basis of data obtained from 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

Chapter 3 Gaps and future scope

3.1 Limitations

After literature review it is observed that a lot of work is done in development of biogas, biodiesel and LPG based dual fuel systems. A lot of research is done for production of biodiesel and biogas and in field of modifications required in IC engines to run them on dual fuel mode using Biogas, biodiesel or LPG. But in the field of gasification of biomass and its use in IC engines, following limitations are noted:

- Little information is available regarding optimization of load conditions and performance characteristics of IC engines run in dual fuel mode using producer gas and diesel blends.
- Very less investigation on testing of gasification process of cotton stalks as a biomass fuel.
- Limited information is available about variation in noise levels of IC when they are switched from normal operation to dual fuel mode.

3.2 Scope of further research

- Because of little data available, there is need to develop a test procedure and analysis techniques on the basis of gasification from biomass so that variation of performance characteristics can be evaluated.
- Comparison of noise levels of IC engines in normal operation and dual fuel mode at different load conditions should be studied.
- Feasibility of cotton stalks as biomass fuel for gasification process can be investigated.

Chapter 4 Methodology & experimental investigation

4.1 Introduction:

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. Basic steps of experimentation are described below:

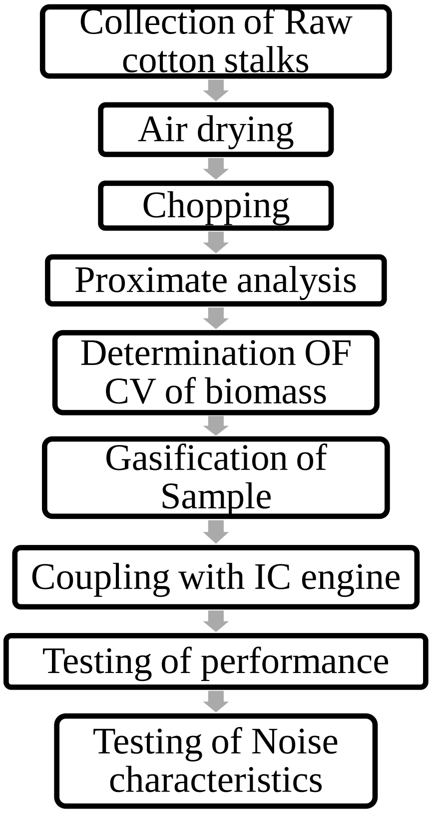

Fig 15 Flowchart of methodology used for experimentation

4.2 Collection of Raw Material

The 40% and 50% of cotton and mustard stalks are available as surplus out of their total stalk generation of 29.4 and 9.4 Mt, respectively according SPRERI (2004). 90Kg of raw cotton stalk was collected from a farmer of Vill. Birewala Distt. Mansa. Raw cotton stalk was air dried for one week. The size of raw stalks varies between 1ft to 3ft.

Fig 16 Raw cotton stalks.

Fig 17 Cotton stalk shredder

4.3 Chopping

Air dried raw cotton stalks are chopped in required size range i.e. below 20mm using a cotton stalk shredder at Satwant Agro Industry Bhawanigarh. The shredded cotton stalk biomass was used as feed material in the downdraft biomass gasifier. The whole cotton stalk biomass was difficult to use directly in the gasifier reactor so the shredded cotton stalk was used as feeding material. The whole cotton stalk plant was converted into shredded material with the help of cotton stalk shredder. Above shows the view of cotton stalk shredder used in the present study. It mainly consists of feeding trough, peg tooth beater, outlet section, electric motor and stand. The shredder is operated with the help of 7.5 hp, 3 phase, and 1400 rpm electric motor.

The capacity of cotton stalk shredder machine is 3.5 kg/min. The machine was operated with the help of two persons, one person is required for supplying the material and another is required for feeding the material into the machine. Three feeding gear are there to obtain different particle size.

Fig 18 Processed cotton stalks ready for gasification.

The processed cotton stalks have moisture content less than 10% and maximum size of processed cotton stalks is 20mm. 10% of processed cotton stalks have size less than 5mm which are helpful in easy ignition of biomass fuel when they are fed into gasifier.

4.4 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. Apparatus required for the process is:

- Ventilated drying oven which is capable of maintaining uniform and constant temperature of 110°C.
- Silica crucible.

- Desiccator for cooling and storage of sample.
- Digital weighing machine.
- Muffle furnace which is capable of attaining high temperatures such as 600°C.

The sample is tested for proximate analysis according to ASTM D7582 – 15 standard. 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 than 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 a desiccator. 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 a desiccator, 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 fixed carbon in the sample is given by the following relation:

FC = Total weight – (Moisture + VM + Ash).

Table 2 Proximate analysis of cotton stalk (air dried basis).

S.No.	Moisture Content	Fixed carbon	Volatile matter	Ash content
1	7.75%	23.42%	64.72	4.11

4.5 Calorific Value

The calorific value of cotton stalk was measured by using an oxygen bomb calorimeter; 1 gm. of briquetted sample was taken in a nichrome crucible. A 15 cm long cotton thread was placed over the sample in the crucible to facilitate in the ignition. Both the electrodes of the calorimeter were connected by a nichrome fuse wire. Oxygen gas was filled in the bomb at a pressure of around 25 to 30 atm. The water (2 lit.) taken in the bucket was continually stirred to homogeneous the temperature. The sample was ignited by switching on the current through the fussed wire and the rise in temperature of water was automatically recorded. The following formula was used to determine the energy value of the sample.

Fig 19 Oxygen Bomb Calorimeter

Formula Used:

CV = (2382.32* T/x) - (E1+E2)

T=change in temperature of water

x=weight of sample (cotton stalk)

E1+E2=weight of Nichrome wire and Cotton thread

Table 3 CV of cotton stalk

S.No.	Weight of water	Weight of Sample	Temp. rise	Correction factor (E1+ E2)	CV of cotton stalk
1	2000 g	1.39 g	2.40°C	121 g	3967.6 cal/g

4.6 Gasifier Setup:

The specifications of the gasifier are provided in table and are in accordance to the catalogue provided by the manufacturer.

Table 4 Specifications of gasifier system.

Parameter	**Specification**
Gasifier Make	Ankur Scientific Energy Technologies Pvt. Ltd.

Gasifier model	WBG-10
Gasifier Type	Downdraft with a throat.
Number of air inlets	2
Start up	Through engine suction/blower.
Fuel Type and Size	Woody Material/Agricultural waste with maximum dimension not exceeding than 25mm.
Permissible moisture content	<20%
C.V. of the producer gas produced	4393.2 kJ/Nm3 to 5439.2 kJ/Nm3
Thermal output	30.21 kW
Typical gas composition	CO = 19±2%, CH4 ≤ 4%, H2 = 18±2%, CO2 = 10±4%, N2 = 51%
Typical Conversion Efficiency	Over 75%
Gas flow rate	25 Nm3/hr (Maximum)
Fuel Consumption	8-10 kg/hr

4.7 Operating Description of system

Fig 20 Gasification system used for study.

4.7.1 General description:

The processed cotton stalks used for gasification are fed through the feed door and it stored in a hopper at the top of gasifier assembly. For partial combustion of biomass fuel air enters from two Air nozzles in controlled and limited amount. Relatively good quality and clean producer gas generation is ensured by the throat (or hearth) of gasifier. The grate holds material for reduction of partial combustion products while allowing the ash to drop off in the ash collection cone. The gas outlet is connected with the engine via scrubber, charcoal filter and safety filter with an air control valve to facilitate running of the engine in Dual- fuel mode.

4.7.2 Gasifier feeding Procedure:

- Fill dry and prepared biomass in to the hopper on the top of this charcoal layer up to the top of the hopper such that the feed door can be conveniently closed.
- Lock the feed door and ensure locking of the ash discharge door of reactor.
- Also check the locks of charcoal filter and safety filter doors. This must be strictly checked as even a minor leakage of air could lead to serious problems.
- Shuffle and level the filter media check its level in the both primary and secondary filters and make it up as needed.

4.7.3 Gasifier Firing and Shutdown Procedure:

For igniting the gasifier following sequence of steps should be followed:

- Before igniting the biomass fuel in the gasifier, plugs of both the air openings are removed.
- Check water level in the cooling tower tank.
- Scrubber pump is switched on, which helps in creating a negative pressure inside gasifier.
- Ignite the gasifier by holding lighted diesel torch at both the air nozzles, one after the other, so the flame is sucked into the nozzles.
- After about a couple of minutes, remove the torch and observe the nozzle through the sight screen to check if there are glowing charcoal pieces inside or else repeat the procedure.
- After successful ignition of gasifier generation of producer gas starts and it can be seen by bringing burning torch near flare of gasifier.
- Blue colored flame at flare indicates that formation of producer gas is started.
- This process can take 5 to 10 minutes.

Fig 21 Air opening with cap on it.

For shutting down the gasifier system following steps should be followed:

- If gasifier is coupled with an engine, stop the engine or switch it to only diesel mode.
- Stop the scrubber pump which reduces pressure difference.
- Absence of negative pressure inside gasifier stops movement of fresh air into gasifier which leads in stopping of partial combustion process.
- Plug the caps into both air openings to block any further fresh air movement.
- Bring the burning diesel torch near flare.
- Absence of blue colored flame near flare indicates stoppage of gasification process.
- Don’t open the lid of biomass hopper until whole set up cools down.

4.7.4 Gas Cleaning Setup:

The gas obtained at outlet of reactor has a high temperature generally near about 450°C, is not pure in nature and contained some amount of tars, so it needs cleaning and cooling before it can be used as a fuel in the dual fuel CI engine. For this purpose a cleaning and cooling unit is employed just at the exit of the gas from the reactor.

Fig 22 Filters for ultra cleaning of the gas

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, H_2S, SO_2 and NH_3. 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. 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.

4.7.5 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.

4.8 Problems faced in gasification system:

- Bridging and jamming associated with handling of feed and / or ash either inside or outside gasifiers.
- 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 engines.
- 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.

4.9 Dual fuel engine setup:

Fig 23 Flow meter used to measure flow rate of producer gas.

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

Table 5 Specifications of the DFCI engine setup.

Parameter	**Specification**
Engine make	Kirloskar
Engine model	AV-1
Engine type	VCRE (Variable Compression Ratio Engine)
Cylinders	1
Strokes	4
Start type	Electric start
Bore	87.5mm
Stroke	110mm
Capacity of the engine	553 cc
Maximum power	3.7 kW at 1500 RPM
Connecting rod length	234mm
Compression ratio	12 -18
Dynamometer	Eddy current type
Dynamometer arm length	185mm
Orifice diameter	20mm
Fuel	Diesel alone and blends of diesel and producer gas
Cooling system	Water cooling

Fig 24 Dual fuel engine setup used for experimentation coupled with a dynamometer.

Precaution should be taken that, it is necessary to open the water supply valve before starting the engine to circulate water in water jackets of engine for cooling purpose and to calorimeter for measurements. The amount of water needed to be supplied to engine water jacket and calorimeter for safe functioning of setup is 250 LPH and 75 LPH respectively.

Compression ratio of engine is kept constant (18) during testing. Air flow and gas flow are recorded using two separate orifices of 20 mm and 15.31 mm diameters respectively. The flow rate of producer gas is kept nearly 5 Nm^3/hr throughout the process with the help of flow control valve. Load is varied from 1 to 11 kg during testing to study variation in performance parameters and noise characteristics at various loads. For purpose of comparison, performance parameters and noise characteristics of engine are tested in two modes:

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

Chapter 5 Results & Discussion

In order to ensure the repeatability and the correctness of the experiment, keeping all the parameters same, three trials of all the tests were taken. For obtaining better graphical presentation, different values obtained at each load are averaged to single value. At both modes, these averaged values are used for making graphs.

5.1 Performance parameters of the DFCI engine:

Variation in various performance parameters such as indicated power, brake power, fuel consumption, brake and thermal efficiency and brake specific fuel consumption is studied at various loads in diesel mode and dual fuel mode.

5.1.1 Indicated power:

Fig 5 shows the trend followed by the indicated power with load variations. In diesel mode, the engine shows a constant increase in the indicated power, but in dual fuel mode, there is a slight reduction in indicated power of the engine due to the fact that the gas has a low C.V. as compared to the pilot fuel.

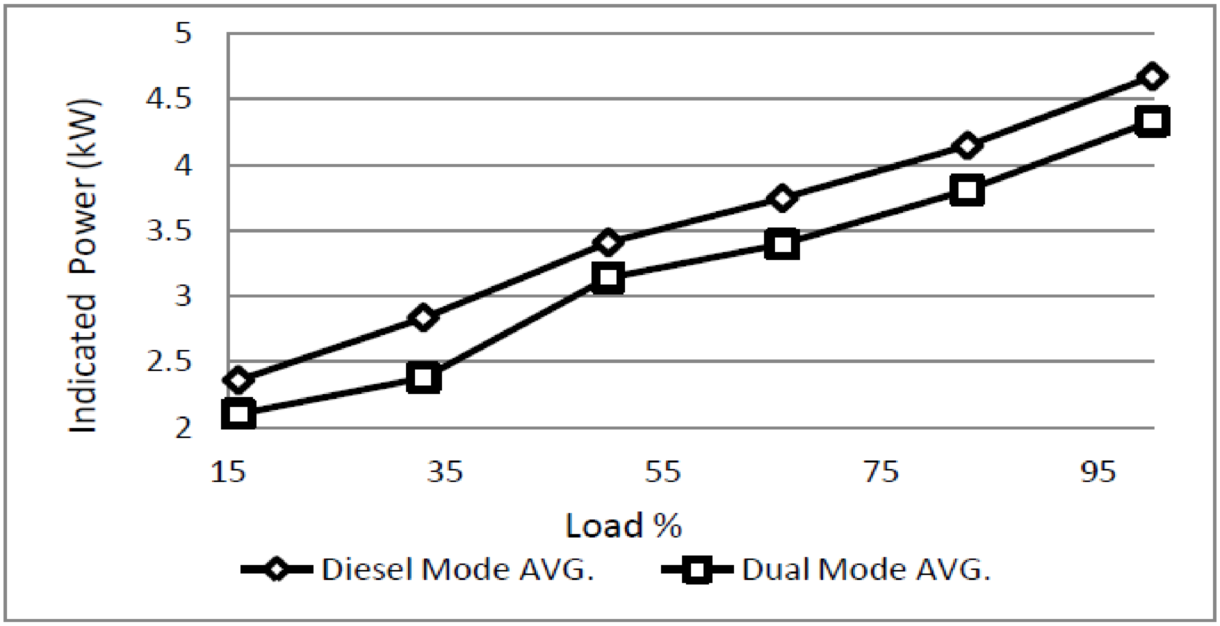

Fig 25 Variations of indicated power at different load conditions.

The highest indicated power produced by the engine was 4.3kW in dual fuel mode, whereas in case of diesel mode highest value of indicated power was 4.67 kW. A maximum reduction of 0.46 kW was noticed at 33% load.

5.1.2 Brake Power:

Fig 26 shows the corresponding increase in brake power of the engine with respect to increase in the load. The brake power increases almost linearly with increase in percentage of load.

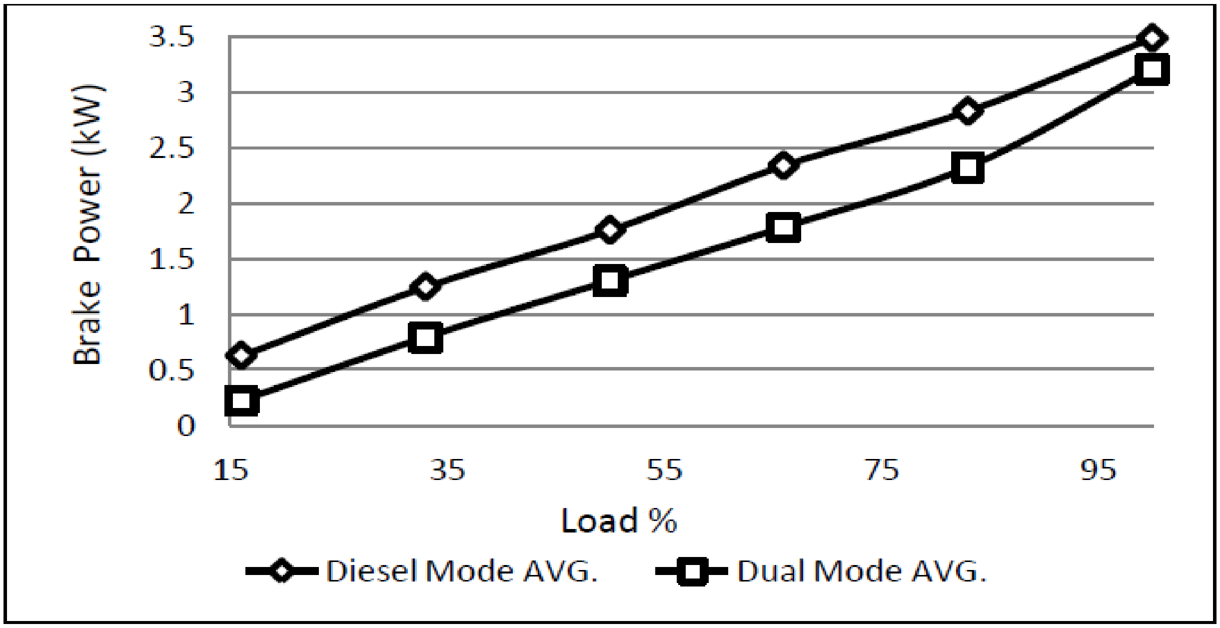

Fig 26 Variations of brake power at different load conditions.

As seen in the earlier case, there was a slight decrease in the brake power produced by the engine due to the low C.V. of the gas. At higher values of load, there was the least reduction in the brake power and the highest brake power produced by the engine was 3.2 kW at the dual fuel mode where as at pilot fuel mode, the maximum brake power of 3.48 kW was produced.

5.1.3 Diesel fuel consumption:

Fig 27 shows the reduction in the diesel fuel consumption with the introduction of mixture of producer gas and air. There is a significant reduction in the pilot fuel consumption due to its replacement with producer gas. In diesel mode, the fuel consumption increases almost linearly to 83% load values, but afterwards it becomes almost constant. Where as in dual fuel mode, at lower loads, the percentage reduction noted, is less as compared to higher loads. This reason behind this trend is the increase in the gaseous fuel consumption. A maximum of 45.4% reduction in diesel consumption is noted in the present study.

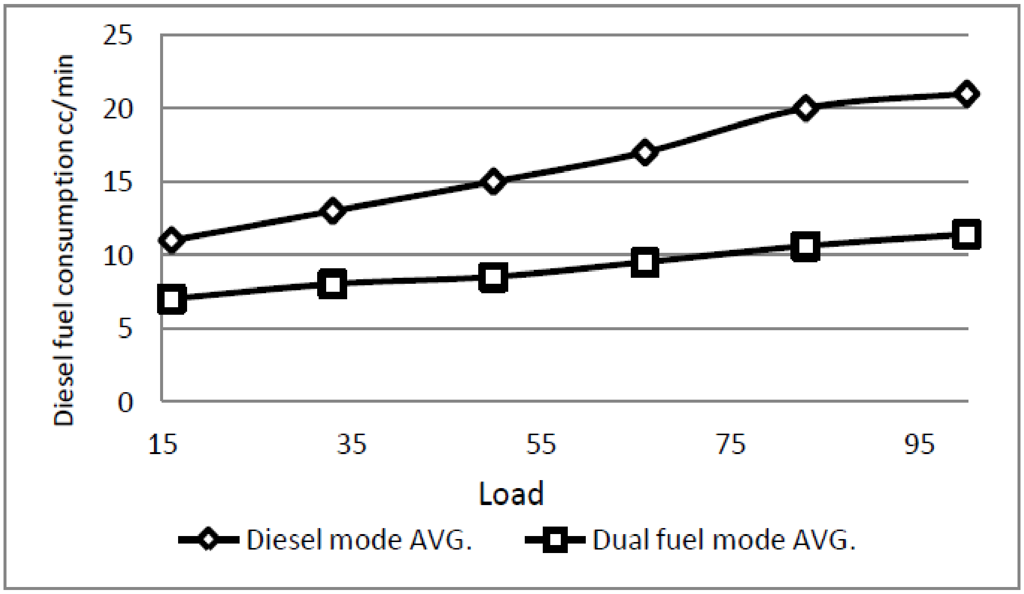

Fig 27 Change in diesel fuel consumption with variation of load.

5.1.4 Gaseous fuel consumption:

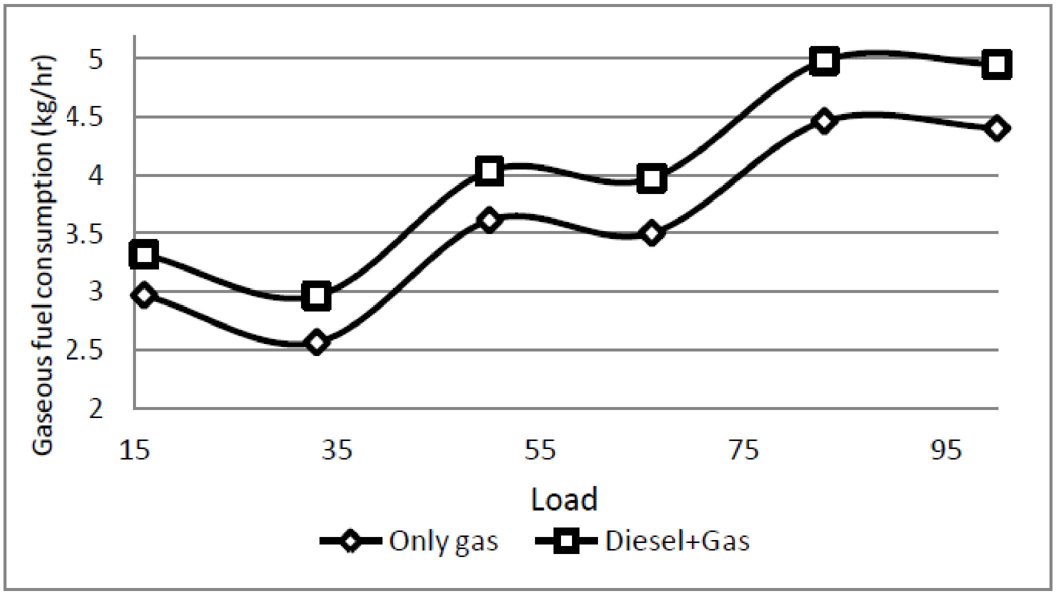

Fig 28 Change in gaseous fuel consumption with variation of load.

Fig 28 shows the trend followed by the gaseous and the dual fuel (mixture) with the load variations. The gaseous fuel consumption shows a wave like nature and doesn't represent a regular trend. It is evident from the fig 8 that the maximum consumption of gaseous fuel was noted higher values of load (>83%). The values of gaseous and mixed fuels are 4.4 kg/hr and 4.9kg/hr respectively.

5.1.5 Indicated thermal efficiency:

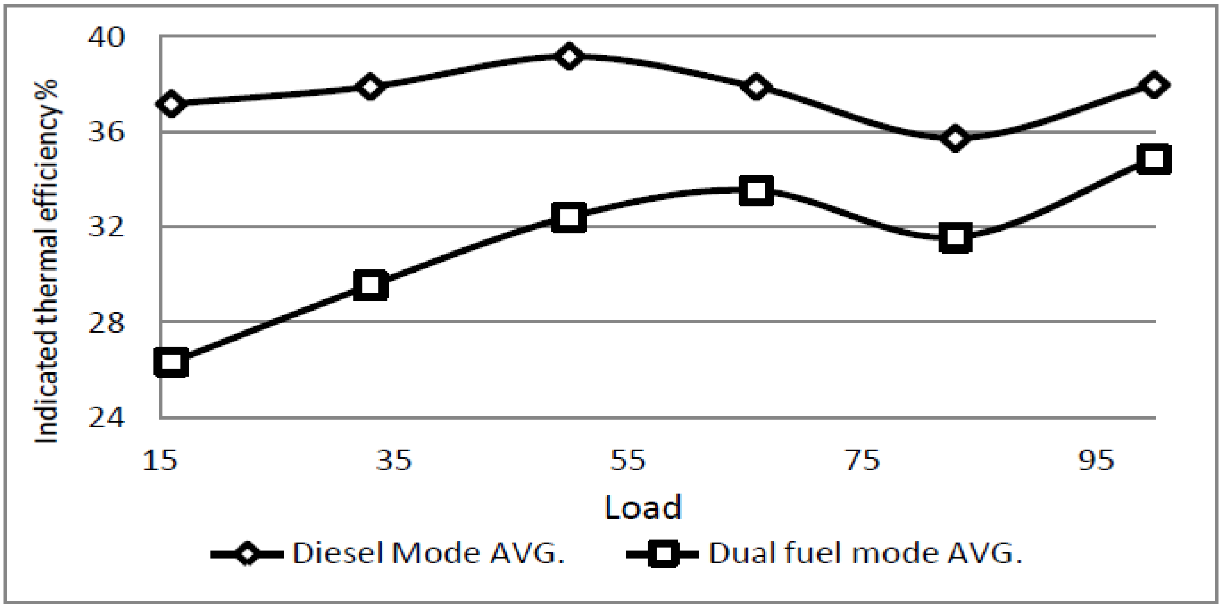

Fig 29 Variation in indicated thermal efficiency with change in load conditions.

The variation of indicated thermal efficiency is shown in fig 9. At diesel mode the indicated thermal efficiency shows a slight linear increase with increase in load up to 50% value, whereas it shows a reverse trend up to 83% load value and it again increases linearly to 100% load value. A similar trend is seen in the case of dual fuel mode. But, at lower load values the engine shows a large reduction in indicated thermal efficiency and this reduction appeared to be diminishing at higher loads. The maximum indicated thermal efficiency of 39.16% was noted on diesel mode at 50% load value. Whereas this value was 34.84% (maximum) at 100% load.

5.1.6 Brake thermal efficiency:

Fig 30 shows the brake thermal efficiency of the engine at the two different modes. The brake thermal efficiency increases almost linearly with increase in load on the engine. Since brake power is proportional to the load on the engine, similarly brake thermal efficiency also shows the same trend.

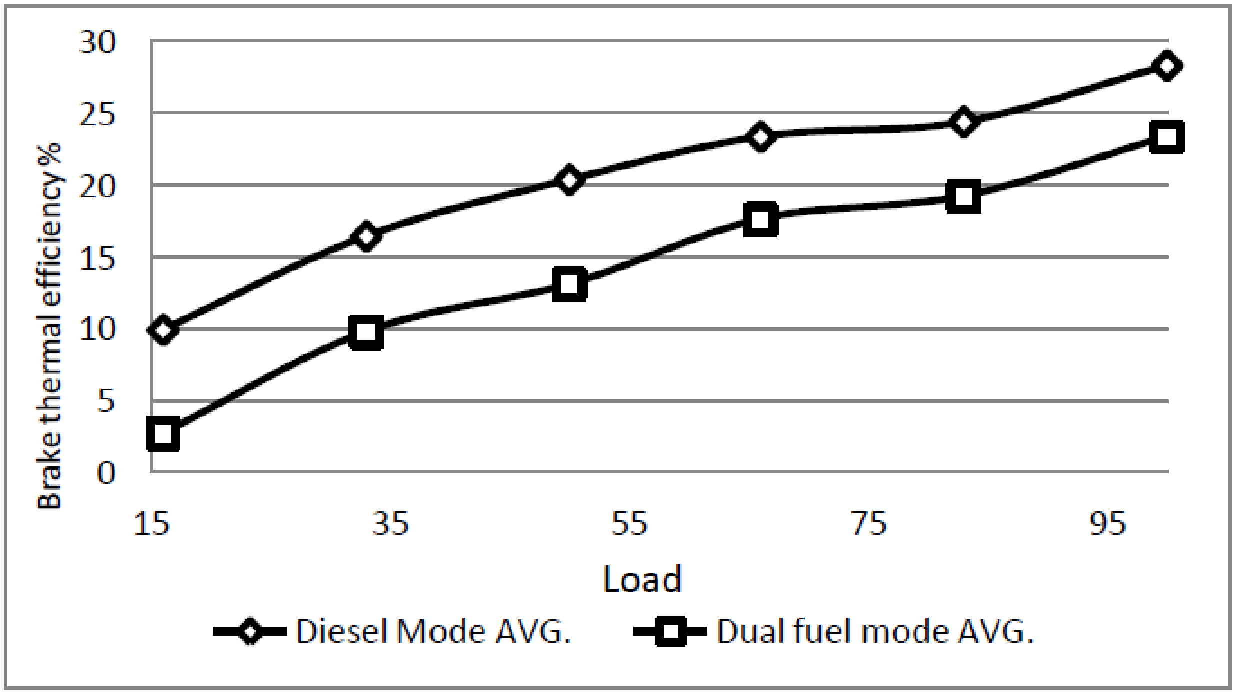

Fig 30 Variation in brake thermal efficiency with change in load conditions.

The lowest and the highest values of brake thermal efficiencies at diesel mode were 9.92% and 28.28% respectively. Whereas in dual fuel mode these values were 2.76% to 23.34%. The reason for this decrease in brake thermal efficiency in dual fuel mode is the low C.V. of the producer gas.

5.1.7 Brake specific fuel consumption (BSFC):

Fig 31 shows the brake specific fuel consumption of the engine with respect to load variations. At both the modes, the engine shows a decreasing trend of BSFC. In dual fuel mode, the engine shows a sudden decrease in the BSFC at ≤33% load, whereas a regular decreasing trend is followed at the higher loads. This is due to the fact that with the increase loads, the brake power also increases and this results in the decrease in the BSFC. The BSFC at the dual fuel mode is higher than the diesel mode due to the low C.V. of the producer gas.

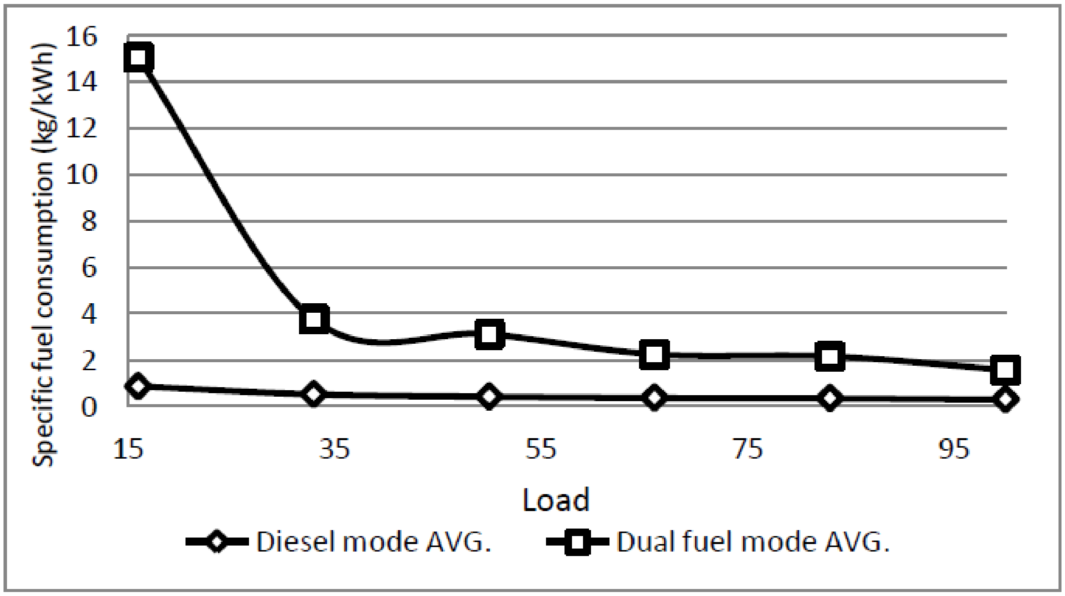

Fig 31 Change in BSFC with variation of load.

5.2Noise characteristics:

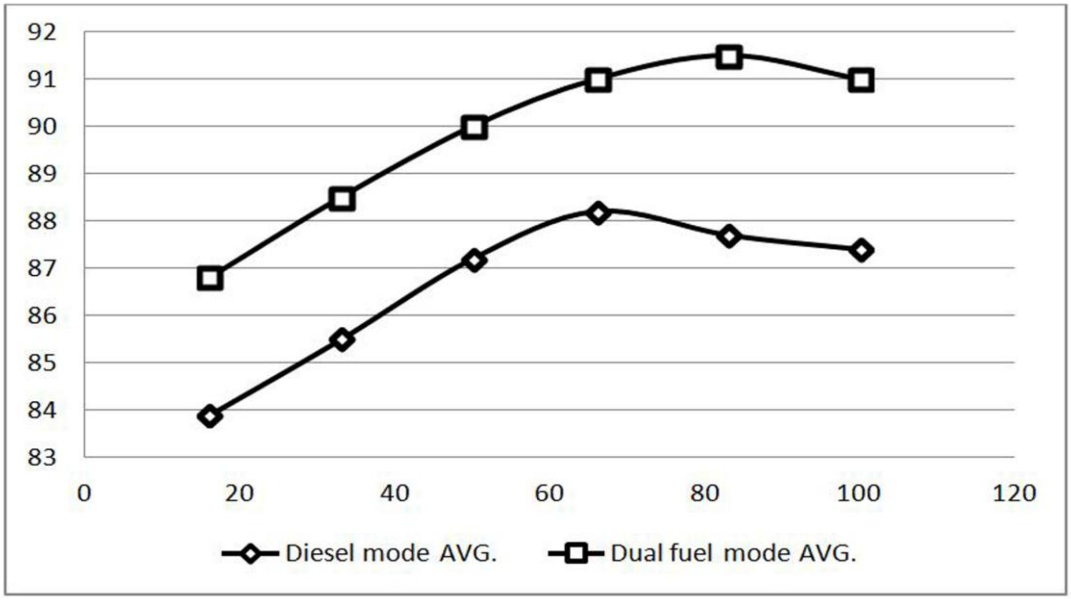

Fig 32 Noise characteristics with respect to load variations

As shown in fig 32, an increase in the noise produced by the engine is noted when operated at high load, but at load >83% the noise levels show a slight decrease in dual fuel mode and this decrease is noted at load >66% on diesel mode. On an average, there is an increase of ~3.4dB of noise levels when the engine is operated on the dual fuel mode.

Chapter 6 Conclusion

- Dual fuel engine is going to be more attractive in coming years to utilize biomass waste.
- Cotton stalk gives the satisfactory performance when coupled with IC engine.
- There was 16.25% and 29.14% reduction in indicated power and indicated thermal efficiency of the engine in dual fuel mode.
- Brake power and brake thermal efficiency were reduced by 16.67% and 24.56% respectively.
- Maximum 45.71% reduction in fuel consumption was noted.
- As noise levels are high in dual fuel mode, so proper noise damping mechanisms are need to be employed to maintain proper working conditions.

Chapter 7 Future scope

- Effect of particle size distribution and moisture content of biomass fuel on the performance of gasifier can be studied.
- Effect of variation in equivalence ratio on gasification parameters can be studied.
- Emission parameters of the agricultural wastes can be analyzed to know their effect on global climate.
- Effect of long term operation on the various components of the engine can be studied.

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