Study of Emission Characteristics and Noise of Dual Fuel Engine Run on Blends of Diesel and Producer Gas from Biomass Materials

A Dissertation

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In

Thermal Engineering

By

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(Harmanpreet Singh)

Dedication

This dissertation with all my heart is dedicated firstly to my **GOD** and my father **L. Harshpal Singh**, who always keep on watching me from that heavenly abode, then to my mother, **Mrs. Surinder Kaur** and grandfather **S. Jaswant Singh** and specially dedicated to my brother-in-law, **Dr Rao Varinder Singh** sister, **Ms**. **Tanveer Kaur** for their continuous motivation, support and moral help.

Ceritification

I hereby certify that this seminar report entitled, **"Study Of Emission Characteristics And Noise Of Dual Fuel Engine Run On Blends Of Diesel And Producer Gas From Biomass Materials"** in partial fulfillment of the requirements for the award of the Degree of Master of Engineering in Thermal Engineering submitted to the Mechanical Engineering Department, Thapar University, Patiala, is an authentic record of my own work and has not been submitted for any degree to any this or any other institute.

Harmanpreet Singh

Date: 30/5/2016 **Harmanpreet Singh**

Place: PATIALA **(801483028)**

This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

Supervisor: **(Dr. S.K. Mohapatra)** 30/5/16

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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
- SB – Suagrcane Bagasse
- VCRE – Variable Compression Ratio Engine
- VM – Volatile Matter

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Summary

In India, the total installed capacity of power generation as on 31st December 2015 is 284303.39MW. The power generated from renewable energy contributes 13.17% of the total power output of which 12.14% power is generated from biomass. India is an agro based country due to which there are large resources of biomass. Biomass is generated in various forms such as agricultural residue, forest waste, sewage sludge, herb residue, etc. The traditional method of direct combustion of biomass is now replaced by the modern methods of processing of the biomass to more compatible and efficient forms followed by their combustion in various combustion chambers. Modern techniques such as pyrolysis, gasification, fermentation, anaerobic digestion and esterification are much more efficient as compared to the direct combustion process. The emission of GHGs (Green House Gases) is the major area of concern. These days due to various problems related to the GHG emissions, these modern concepts are getting more and more attention. The processed/compatible products such as wood oil from pyrolysis, synthesis gas from gasification, bio-ethanol from fermentation, biogas from anaerobic digestion, biodiesel from esterification are able to replace the conventional fuels, i.e. coal, petroleum and natural gas to a large extent. These biofuels are helpful in the reduction of the use of conventional fuels and also reduction in GHG emissions. Due to increasing use of conventional fuels and an improper utilization of biomass, air pollution and GHG (Green House Gas) emissions are the major areas of concern. Due to this, the world is now interested in shifting towards the synthesis and use of alternate fuels, that can replace the conventional fuels. This report is based on literature review/survey of "**Production of producer gas from various available biomass materials".** A brief introduction to the basic gasifier system and characteristics of producer gas being produced is presented in this report. This report lays emphasis on the proper and efficient use of producer gas in a dual fuel engine along with blends of diesel. Such an experimental investigation was carried out in which, biomass materials like, sugarcane bagasse along with carpentry waste in 1:1 ratio were used to sythesize producer gas in a downdraft gasifier with a gas flow rate of 5.07Nm^3/hr. By blending this gas with diesel it was fired in a dual fuel CI engine, which showed a smooth working and was tested for 6 load variations for noise characteristics and various performance and emission parameters. A maximum of 45.7% and 69.5% reduction in fuel consumption and NOx emissions respectively was reported with a slight increase (~3.4dB) in the noise. Some research papers related to the study of production of producer gas are also presented in this report. Problems and limitations related to the available literature are listed in this report. Some solutions are also suggested at the end of this report.

Chapter 1 Introduction

In India the energy consumption in the commercial area is growing with a fast pace. Due to increase in population and industrialization, fossil fuels are getting depleted at a fast rate. The major the energy requirements of India are met by coal and oil. So now there is always a risk of further diminishing of the sources of these conventional fuels.[1] In the domestic sector, energy is consumed basically in terms of coal and kerosene. These fuels appear to be problematic not only due to emissions related to GHGs (Green House Gases) but also, these are fast depleting energy sources. There is a tremendous increase in the imports of petroleum and coal, due to the high growth in the economy of the country, resulting into the contribution in the increase of the import bills. In lieu of this, it has become a need on the side of researchers and energy planners, to develop such systems, which can shift the commercial energy consumption on alternate and renewable sources of the energy.

The major renewable energy sources such as wind energy, solar energy, hydel energy, bioenergy including the energy recovered from waste originating from municipalities and industries are available freely and in an ample amount. India is a rich country in terms of natural resources. Many big projects are already running on the harnessing of solar, wind and hydro energy.

Due to the polluting nature of conventional fuels, biomass energy or simply bioenergy seems to be attractive in providing alternative and renewable energy solutions to commercial and industrial regions. Bioenergy systems can be easily used to meet the power requirement of industries and rural regions. This alternate power generation will support the industries to become self-dependent thereby reducing the pressure on conventional fuels. At present, energy units based on bioenergy having a capacity of about 100 kW to some MW are easily available to be set in any industry.

As far as the environment is concerned, biomass is more advantageous as compared to the conventional fuels such as coal and petroleum. In biomass, sulfur and nitrogen are present in very small amount, so it doesn't participate in causing the acid rain. When biomass is burned, directly or indirectly, carbon in the form of CO_2 is returned to the atmosphere. The plants consume this CO_2 for their food and their growth, thus creating a loop. Due to such issues with the conventional fuels, the interest in the alternate renewable fuels is gaining more and more popularity these days. [2]

Research is ongoing on harnessing energy from biomass obtained from various sources such as coconut shells, rice husk, cotton stalk, woody biomass etc. The traditional technologies using biomass are grossly inefficient. There is, therefore, ample scope to utilize biomass more productively by its conversion to some alternate fuels. These fuels are obtained by any one or combination of more than one of the following processes: [3]

Table 1 Classification of biomass conversion techniques [3]

Technique	Raw Material	Major Product
Pyrolysis	Woody biomass	Bio-oil
Gasification	Any kind of dry biomass	Producer gas
Anaerobic Digestion	Vegetable waste, animal dung and litter	Bio-gas
Fermentation	Forestry waste containing sugar, starch or cellulose example: molasses, beet roots, etc.	Bio-ethanol
Esterification	Non-edible vegetable oils and waste cooking oil example: jatropha oil, neem oil etc.	Bio-diesel

The average yield of the products in each process ranges from 60% to even 95% of the mass of raw material used.[4] These fuels are a more compatible form of the biomass, due to which these are flexible enough to be used in a number of energy generation devices. The generation and thereby combustion of these products have replaced the conventional fuels to a great extent in most of the developed countries.

These fuels serve a good purpose in co-fired furnaces and combustion chambers.[6–8] Liquid and gaseous fuels can be very easily used in IC engines, which are more efficient and robust.[9,10] Apart from combustible products, a variety of chemical substances such as alcohols, esters, organic acids, ethers, gases like hydrogen, carbon dioxide, etc. can also be produced, which find their use in chemical industries. These processes are cost effective in nature as biomass is freely available and in a large quantity in agro based countries.[10] It can be said easily that in today's world, almost everything can be produced using bio-fuels and bio-chemicals or simply "biomass".

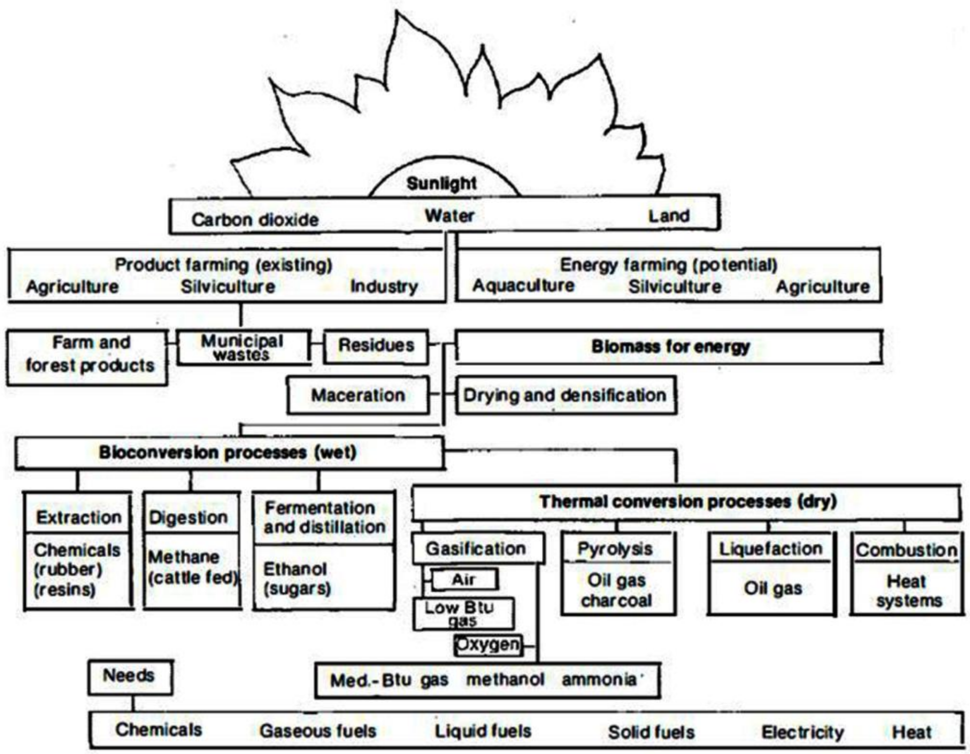

Fig 1 Flow chart showing the flow path of bioenergy [5]

The technologies of gasification through thermochemical route, biomethanation and destructive distillation are some of the alternative routes which are being increasingly accepted as the viable alternatives to the conventional energy technologies for the decentralized sector. While cellulosic material with high moisture content is more suitable for biomethanation, biomass with higher lignin content and low moisture is more suited for thermochemical gasification. The two technologies are, therefore, largely complimentary.

Both biogas from biomethanation and producer gas from gasification could be used in internal combustion engines for motive power or electric power generation. Although the biogas has a calorific value higher than the producer gas, gasification has a distinct advantage for power generation: the rate of biomethanation is much slower than gasification and hence continuous power generation becomes difficult with the requirement of very large storage of biogas. On the other hand, there is no need for storage of producer gas: by proper system design, the capacity of the gasifier can be matched with the capacity of the engine. The on-line generation of gas, as per the requirements of the engine, makes the system more convenient and compact to use. [11]

Keeping this fact in mind, biomass appears to be promising energy resource for future power generation. Due to lack of awareness among the farmers and less available techniques, the biomass is not used efficiently in India. The agri-waste is either burnt in open or just thrown away as a waste at the dumping sites. Biomass is mainly burned in open or in open stoves called as “chullahs”. These traditional stoves produce a lot of smoke, which is harmful for both the user and the environment. The smoke causes problems such as irritation in the eyes and nose. It is also responsible for the formation of “smog”. In the past time, biomass or bio-energy projects were not given many incentives as compared to solar or wind energy projects. But now days, the biomass based energy projects are becoming quite popular. These projects are also quite economical because biomass is freely available and in plenty and the most important, it is “renewable”. [9]

As per the installed capacity report published by Ministry of Power, Govt. of India as on 31.11.2015, 70% of energy is generated from fossil fuels and 28% is generated using RES, including hydel power (15%) the remaining 2% is accounted for nuclear power. Fig. 2 depicts the percentage share of various resources of energy in India up to 31st November 2015. At present only 1.61% of the total power is generated from biomass/biofuels.

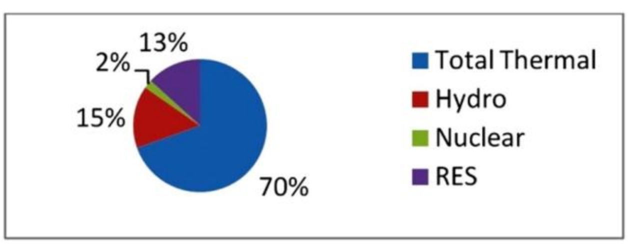

Fig 2 percentage share of various resources of energy in India [12]

Chapter 2 Literature review

Basic Components of Gasification Process:

The basic components of a gasification process are:

2.1 Biomass:

Biomass is biochemical matter derived from either living, or dead organisms.[13] The chemical analysis of woody biomass shows that it is composed of the following components:[14]

- Cellulose:

It is a fiber structured constituent, which is responsible for the strength of the woody biomass. It forms 40-50% by weight part of dry woody biomass. A cellulose molecule is a high weight molecule which is formed as a result of natural polymerization of glucose molecules in a large number. A single cellulose molecule contains 5000-10000 units of glucose. The thin microfilms of cellulose twist around each other to form a tubular structure. The moisture content in the biomass is contained in these tubes, which produce an explosion sound when heated rapidly. The breakdown of cellulose takes at a temperature of 240^{o}C – 360^{o}C. At this temperature range, the maximum part of the cellulose is converted into volatile compounds. Apart from volatile components, some part is converted into tars and chars, which can be solidified for further use.[15]

- Hemicellulose:

This is another important component of the woody biomass, which comprise 25-30% by weight of the dry biomass. This molecule possesses a relatively low weight (molecular) in comparison to cellulose. It contains only ~150 units of monomers. Unlike cellulose, hemicellulose is a heterogeneous polymer, which is composed of various monomer units. Hemicellulose is also known as polyose. The polymer chain consists of a branched structure. This component decomposes at a relatively low temperature of 200^{o}C – 260^{o}C. In this process, the percentage of volatile components formed is more as compared to tars and chars. Also the volatile yield is more as compared to cellulose.[16]

- Lignin

It is the third important part which accounts for 16-33% by weight of dry biomass depending upon the type of biomass. The hard biomass materials contain a lower percentage where as soft biomass materials contain a relatively high percentage of lignin. It is amorphous in nature, so it can exhibit more than one structure. The exact structure of lignin molecule is not known, but it forms a highly branched three dimension chain. In nature, lignin exist in two different forms – guaiacyl lignin and guaiacyl syringyl lignin. The first type is mainly found in hard biomass materials and is formed on polymerization of coniferyl phenylpropane units. The latter one is formed as a copolymer of coniferyl and sinapyl phenylpropane. This component breaks down at a temperature range of 280^oC – 500^oC into phenols and a greater percentage of chars. The liquid obtained on pyrolysis is called pyroligneous acid. It contains 20% water and 15% residual chars.[17]

- Inorganic minerals:

These materials are found in a very low percentage. They do not contribute in any volatile yield and in the end they form very little amount of ash. In typical biomass composition, minerals like potassium, sodium, phosphorus, calcium and magnesium are found. [18]

- Organic components:

These components are found in traces in woody biomass materials. These components include sugars, fats, proteins, waxes, gums, resins, vegetable oils etc. these components helps the plants to get immunity against insect attacks and serve as energy reserves.[19]

On the basis of the moisture content, biomass resources are classified into two categories:

- Wet Biomass:

  Molasses [20–23], sludge [24–27], fresh forestry waste [21,28], starch [29], and manure [30,31].

- Dry Biomass:

  Old forestry[32] and agricultural wastes[33,34] and residues.

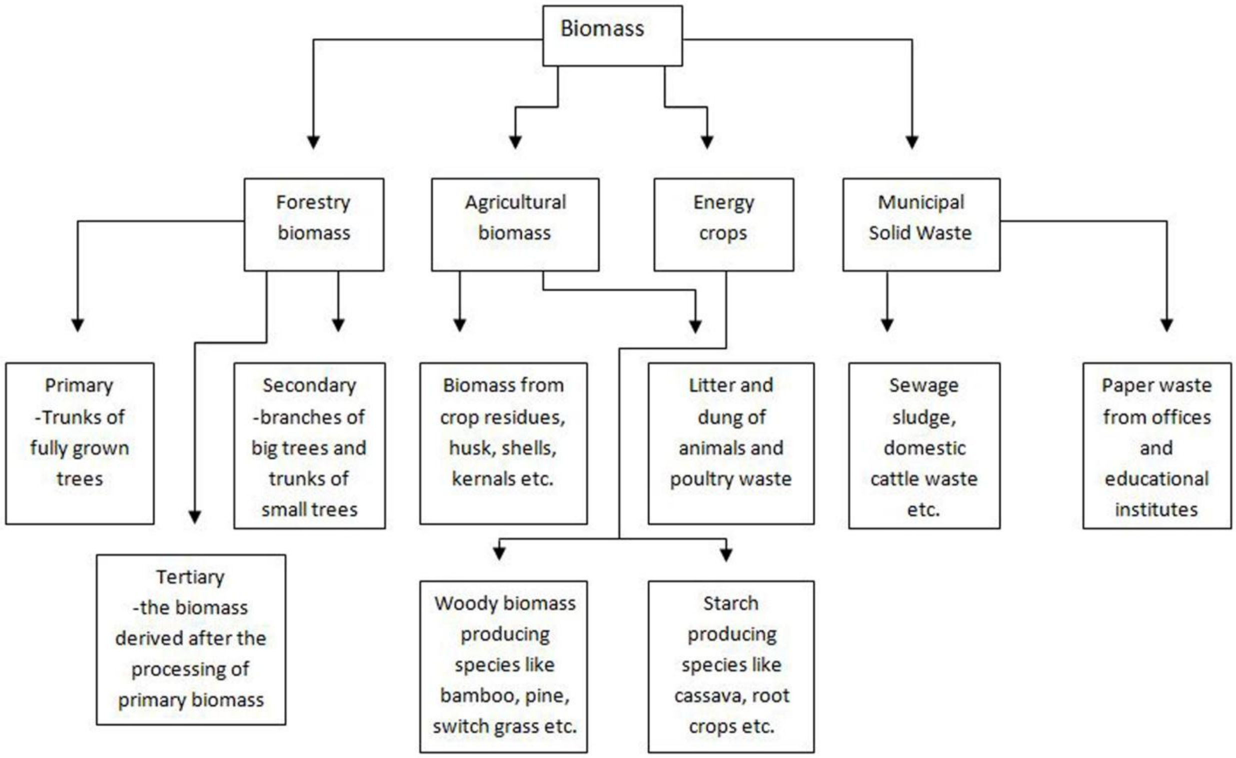

Fig 3 Classification of biomass

Biomass is a renewable fuel which is available from various sources. These sources are classified into four major types as shown in Fig 3:

1. Forestry biomass

2. Agricultural biomass

3. Energy crops

4. Municipal solid waste [35]

2.2 Gasification:

2.2.1 Background:

Gasification is a very old technique of biomass conversion used since last 180 years. Since that time the process of gasification of biomass into combustible gases is used in blast furnaces. This process is popular and emerging in most of the European countries. At present, these projects use peat and other low quality coals as the feedstock. The first gasification system was seen working in 1839 and this gasification system was coupled to an IC engine in 1881. [36] For this process, down draft gasifiers were used. Before World War II, the petroleum was used as a fuel for automobiles and industries, but during the World War II, the world faced a scarcity of petroleum, so the concept of gasification was introduced again. Vehicles were made to run on gas by 1945. According to the survey, around 90,00,000 vehicles were running on producer gas at that time. Due to a sudden decrease in the prices of fossil fuels, this concept started fading out after World War II. Due to the crises in 1970's, this concept again became popular. [37]

2.2.2 Methodology:

The biomass materials used for gasification, include forestry waste, agricultural waste, sewage sludge, herbaceous waste, etc. [28] These wastes at their initial stage contain a lot of moisture, so it becomes difficult to subject these materials in the gasification process. [38] There is a great irregularity in the shape and size of these materials, so they are chopped to smaller regular sized particles or pieces using a chopper depending upon the type of gasification system used. [39,40] The excessive moisture content is removed using various drying techniques. The dried and chopped biomass is fed into the hopper using a conveyor or fed manually. These raw materials, then undergo partial oxidation in a limited supply of air/oxygen to form the syngas.[41]

2.2.3 Working conditions:

As discussed earlier, the biomass materials values of moisture (>50%), to make these materials compatible for gasification process, these are dried using various drying methods to a final moisture of <20%. The biomass is allowed to burn in a limited supply of air to a temperature ranging from 850^{o}C to a maximum of 1100^{o}C. The moisture and temperature condition of 20% and 900^{o}C are optimal for high C.V. gas production. [42]

2.2.4 Process insights:

Gasification is thermo-chemical partial oxidation process, in which the carbon rich material present in the organic substances is converted into combustible gases, i.e. CO, H_2, CH_4

N_2 and CO_2 [43] In this process, biomass is burnt in a closed chamber, which has a restricted supply of air/oxygen and in some cases steam also. Due to this limited supply, biomass doesn't get burned completely. In gasification, partially oxidized products (CO etc.) are formed, which can be oxidized further to get a significant amount of energy. It is the typical process of burning biomass in a reducing type of atmosphere to a temperature of around 850°C. Fig 4 shows the schematic diagram of the basic gasification system.

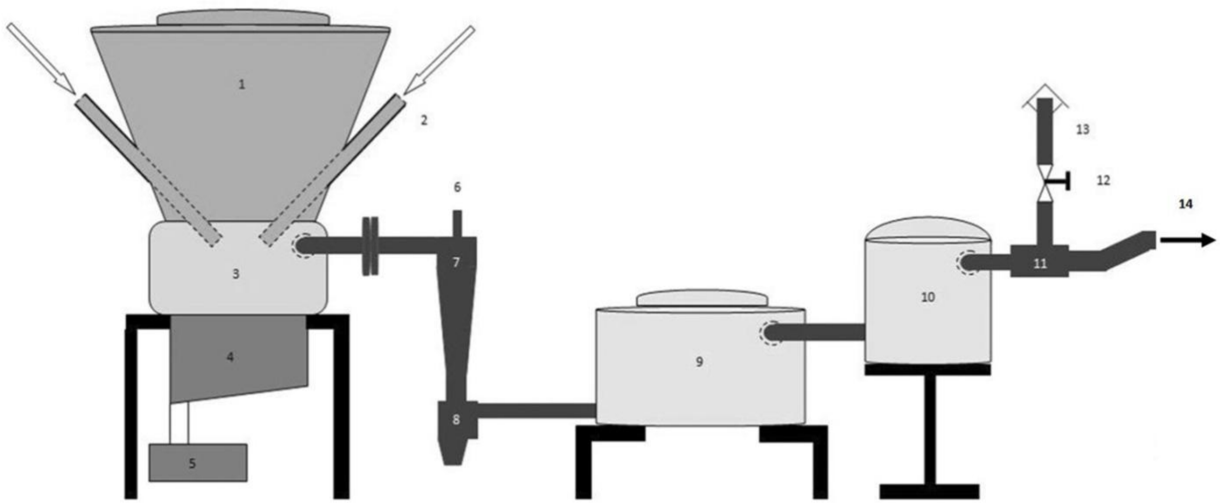

Fig 4 Schematic diagram of the basic downdraft gasification system coupled with cleaning system 1: Hopper and Zone 1 – Drying & pyrolysis, 2: Air inlet, 3: Zone 2 – Combustion, 4: Zone 3 – Reduction, 5: Drain tub for ash removal, 6: Water inlet for the scrubber, 7: Scrubber for cooling and cleaning of gas, 8: Drain box, 9: Secondary filter for tar, particulate and moisture removal, 10: Safety filter for ultra cleaning of gas, 11: Bypass valve, 12: Flare control valve, 13: Flare burner for testing gas quality, 14: Gas outlet for its further use

Biomass materials like wood, forest wastes and agricultural residue are composed of lignocellulosic matter, which are further composed of carbohydrate monomers. These components are partially oxidized to CO, CO_2, H_2, CH_4, etc.

The gasification process is divided into four subparts or zones:

2.2.4.1 Drying zone:

It's the top most zone in the gasifier. As the name indicates, it is the zone where the excessive moisture in the biomass gets dried off. This zone has a temperature of 100°C to

130°C. In this zone, no chemical reaction takes place, but some amount of moisture along with the volatiles leave the biomass in this zone. [44]

2.2.4.2 Pyrolysis zone:

This zone is located below the drying zone. In all the processes in which thermal breakdown of the biomass takes place, pyrolysis is the basic and the necessary step. In this zone, the lignocellulosic matter gets pyrolyzed i.e. it is converted into char and other volatiles like CO_2, CH_4, CO and C_nH_n. In this zone, the temperature of the system gets elevated, to 220°C-250°C. [45]

2.2.4.3 Combustion zone:

The pyrolyzed biomass is now introduced into the combustion zone, where the biomass gets a limited supply of oxygen. The actual and controlled combustion of biomass, oxidizes it to char, tar, and gases like CO, CO_2, CH_4, etc. and other hydrocarbons. The temperature of this zone ranges from 850°C to 900°C. [46]

2.2.4.4 Reduction zone:

In this zone the actual gasification of the biomass takes place. All the compounds, i.e chars, tar, CO, CO_2, CH_4, etc are reduced to CO, H_2 CH_4 and CO_2. N_2 from the air also accompanies these gases, but due to the low temperature of the combustion chamber, it doesn't take part in the reaction and behaves like an inert gas. Random dissociation and recombining of these compounds can be seen in this zone. [47] Mainly four type of reactions are seen in this zone. These are: Boudouard reaction, methanation reaction, steam reforming reaction and water-gas reaction.Various types of reactions, which take place in the gasification process are shown in table 3 along with their change in enthalpy.

Table 2 Various chemical reaction during the gasification process [48]

Process	Chemical reaction	Change in enthalpy (kJ/mol)
Partial oxidation	$C + ½O_2 \rightarrow CO$	−110.50
Complete oxidation	$C + O_2 \rightarrow CO_2$	−393.50

Reaction with hydrogen	$C + 2H_2 \rightarrow CH_4$	−74.80
Reduction of carbon dioxide	$C + CO_2 \rightarrow 2CO$	172.40
Partial oxidation with Steam	$C + H_2O \rightarrow H_2 + CO$	131.30
Water-gas reaction	$CO + H_2O \rightarrow H_2 + CO_2$	41.10
Methanation	$CO + 3H_2 \rightarrow H_2O + CH_4$	206.10

2.2.4.5 Types of gasifier systems:

Depending on the design of the feeding system and the direction of flow of gas, the gasification systems are classified into the following types:

- Downdraft gasifier:

It is a further classification of the fixed bed gasifiers. As the name indicates, it is the gasifier system, in which both the raw materials and the gasifying agent move in a down direction, as a result the gas produced also travels in a downward direction. The air inlet manifolds are inclined in such a way that the air enters the combustion chamber flowing in a downdraft direction. The drying and the pyrolysis of the biomass takes place due to the heat of the combustion chamber in these gasifiers. These gasifiers are also known as “co-current” or “concurrent” gasifiers. Due to downward flow of the gas, it doesn’t come in contact with the excessive tars which are produced in the pyrolysis zone, so less fractions of tars are found in the gas produced in downdraft gasifiers. [49]

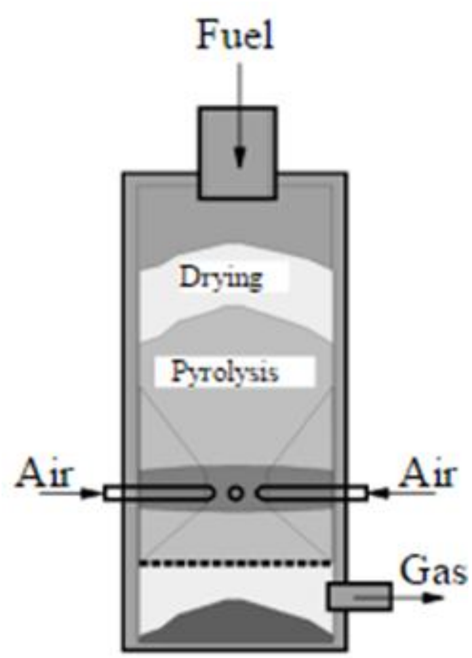

Fig 5 Downdraft gasifier

- Updraft gasifier:

It is also a fixed bed gasifier, in which the raw materials, travel in a downward direction, where as the gasifying agent, i.e. air is introduced from the bottom of the gasifier.

In these gasifiers, the air travels in an upward direction, and so is the direction of the producer gas. In these gasifiers, there are well defined pyrolysis and drying zones and the hot gas, which passes through these zones supplies the enough heat to carry out various reactions, which take place in these zones.

Since the gas passes through the pyrolysis and the drying zone, due to this the gas gets laden with tars which are produced in these zones. Some fraction of the tars collected by this gas from the pyrolysis zone is trapped in the drying zone, whereas the maximum fraction of the tars is transported out with the gas, due this, high amounts of tars are produced in these gasifiers. These gasifiers are also known as "counter-current" gasifiers. [50]

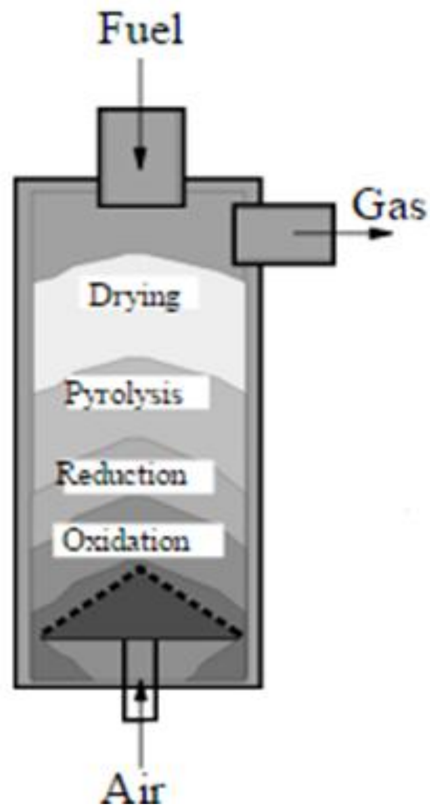

Fig 6 Updraft gasifier

- Fluidized bed gasifier:

It is an another type of gasifier, in which both the fuel and the air are supplied from the bottom with different inlets. These types of gasifiers use fine crushed/milled biomass so that it can be easily fluidized. The different zones like drying, pyrolysis, combustion and reduction zones are not well defined. Since the temperature of these gasifiers is quite low, so a reactive fuel suits better for these gasifiers. In these gasifiers, the particles or more specifically the carbonaceous matter suffers elutriation, i.e. the phenomenon of combining of smaller particles to form bigger and heavier particles, as a result of which, they

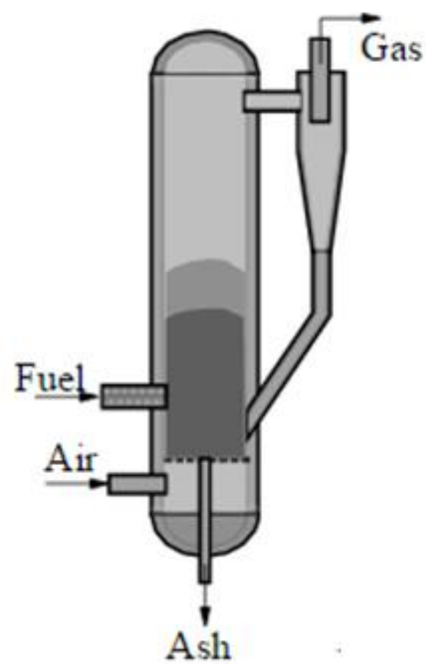

Fig 7 Fluidized bed gasifier

fall back and don't participate in the gasification process. Due to this, the carbon converting efficiency of these gasifiers is less as compared to the fixed bed gasifiers. [51]

- Entrained flow gasifier:

In these types of gasifiers, the milled fuel is entrained into the gasifier with the help of a constant supply of steam and oxygen. The gasification process takes place in a co-current fashion in a downward direction. Since these gasifiers operate at high temperature and pressure, so the use of air in these gasifiers is not preferred else it would result in the formation of NOx, which is not desired. The ash formed at high temperature, gets fused and is collected in the form of slag. Due high temperature of operation of these gasifiers, tars and methane are not formed, i.e. only H_2, CO and CO_2 are the products of these gasifiers, including traces of H_2S, which can be removed by acid cleaning. [52]

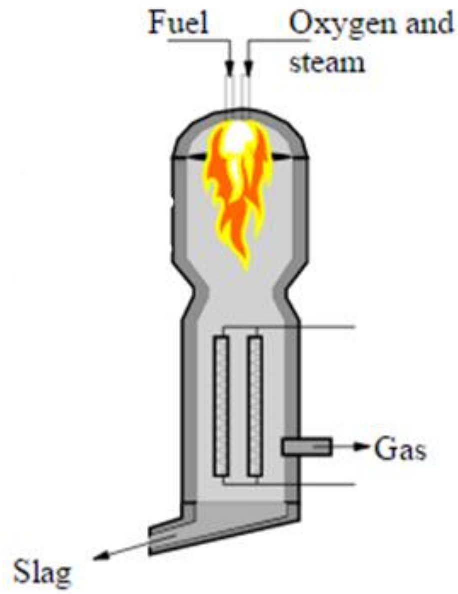

Fig 8 Entrained flow gasifier

- Plasma gasification:

Although this is not a new concept, yet some recent modifications in the conventional gasification system have made this technique more popular and emerging these days. It came into existence ~30 years ago. It is a mixed apparatus having properties of both downdraft and updraft gasifiers. Like the downdraft gasifiers, the fuel as well as the gasifying agents move in the downward direction, whereas the

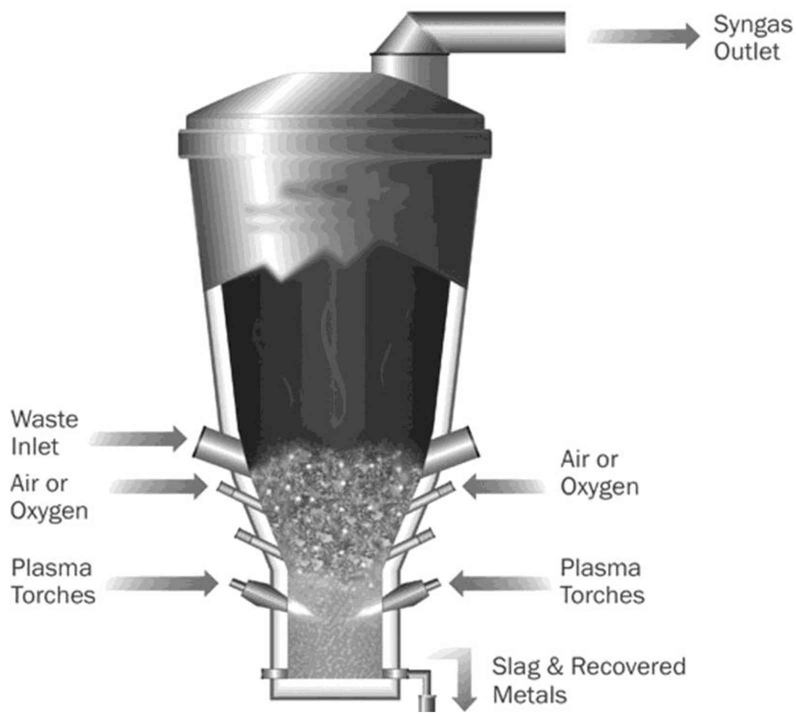

Fig 9 Plasma gasifier [53]

gas moves in the upward direction. It is a high temperature process, in which the plasma torch or arc is used to burn the biomass waste. High moisture (50% - 60%) biomass wastes such as fresh forestry waste, agricultural waste, wet sewage, etc. and rubber tires can be easily used in such gasifiers. The ash at ~3000^{o}C fuses into glassy slag, which has its own applications. [53,54]

The gas which is available at the exit of a gasifier is called as raw gas. This gas is very dirty as it contains a lot of dust, NH_3, HCl, H_2S, SO_2 and some volatile compounds like aerosols and alcohols, collectively called as tar. [55] In order to make this gas compatible for further use in any combustion system, it needs some initial cleaning. This objective is obtained by certain washing mechanisms as explained in the following section:

2.2.4.6 Gas cleaning and cooling:

As explained earlier, the gas needs cleaning and cooling especially, when it is to be used in an internal combustion engine. The gas output available at the outlet of the gasifier has a temperature of ~450^{o}C and it contains a variety of volatile compounds such as hydrocarbons, oxides of sulfur, H_2S, HCl, etc. Which makes it incompatible to be used further in another system. The various parts of the cleaning unit are as follows:

- Scrubber:

It is the unit in which the gas after leaving the gasifier first enters. Initially the gas has a temperature of ~450^{o}C which is cooled using the cold water. In this unit, the gas is allowed to pass through a jet of cold water, which cools the gas and washes particulates, dust and gases like HCl, H_2S, SO_2, NH_3, etc. as these are soluble in water. Apart from this, some part of tar is also washed in the scrubber. [56–58]

- Secondary filter:

After the washing of the gas, the gas is now allowed to pass through the secondary filter. Secondary filter is a drum like structure, which contains mixture of wood powder and wood chips. The gas passes through the voids in the particles, whereas the particulate matter is trapped. The excessive moisture if any is also absorbed by the filter materials. These filters give a 99% pure gas at a temperature of 40^{o}C – 50^{o}C. [59–61]

- Safety filter:

In order to get an ultra clean supply of the gas, the gas is further passed through a safety filter. It is smaller in size as compared to the secondary filter. It contains a paper filter, which is capable to absorb very small soot particles to ensure an ultra clean supply of gas. The gas, after passing through the safety filter becomes 99.9% pure and the temperature of the gas ranges from 30^oC – 40^oC [62,63]

2.2.5 Products of the process:

The gasification process if expressed in a single reaction will be:

$C_6H_{10}O_5 + O_2 \rightarrow CO + CO_2 + H_2 + CH_4 + C_nH_m$ + Heat. [48]

In the gasification process, mainly three types of products are produced: producer gas, tar, char. These are explained below:

2.2.5.1 Producer gas:

It is the major product of the gasification process. On an average the yield of producer gas ranges from 80%-98%. [26,46,58,64,65] As discussed earlier, it is composed of CO, H_2, CH_4, CO_2 and N_2. In an air blown gasification process, CO and H_2 contribute around 30-35% by volume of the total gas mixture. N_2 (present in the air) behaves as an inert gas at 850-1000^oC and comes unreacted with the gas mixture. $N_{2,}$ CO_2 and CH_4 are present in the fractions of 50-55% 15-17% and 3-5% by volume.

2.2.5.2 Tar:

Tar is a byproduct of the gasification process, which is composed of aromatic hydrocarbons such benzene, its derivatives, resins and some alcohols. [66] The term C_nH_m in the above equation corresponds to the fraction of hydrocarbons produced. These include other the aromatic compounds which condense into a dark colored viscous liquid contributing to the tar formation.

2.2.5.3 Ash:

Ash is an another byproduct of the gasification process, which is generated in a very small amount. Since the biomass materials contain very less ash content, so the ash is generated in a very less amount.

2.3 Dual fuel engines:

Due to the shortage of conventional fuels during the World War I, the concept dual fuel engine was introduced by Dr. Diesel, after experimentation on his own made diesel engine. [67] Although these engines came into existence a long time before, but they got attention after world war I. [37] As the name suggests, a dual fuel engine is the one, which uses two types of fuels, out of which, one of the fuel is gaseous in nature and the other is the liquid one. In many cases, both the fuels are gaseous in nature, but at least one of the fuels is gaseous in nature. [68] At the time of the world war I, infrastructure was developed enough to generate a significant amount of natural gas. Due to lack of developed resources, its use was limited to household purposes, or in some of the steel industries. [29] But due to certain circumstances, it found its application in the dual fuel engine. Nowadays, due to its non polluting nature, it's highly recommended to run both light and heavy vehicles on natural gas, as far as possible in the highly populated cities. [69]

Although the gaseous fuels such as LPG (Liquefied Petroleum Gas), Natural gas, etc. require a high compression ratio, yet they have enough self ignition temperature, that the combustion is self sustained in most of the cases. [70] Those cases, in which the combustion doesn’t take place at its own, are initially ignited by a conventional fuel and the engine run on the gaseous fuel afterwards. [71] Due to the robust nature and heavy duty of diesel engines, these can be easily run on various liquid fuel and even crude oil. [72,73] Due to the high compression ratio of the diesel engine, the duel fuel engine is preferred to be made out by modifying existing diesel engines. At both the dual fuel mode as well as the single fuel mode, the diesel engines respond very quickly to the variations in the load, speed as well as to the change in the supply and the nature of the fuel.

2.3.1 Alternate gaseous fuels:

There are various types of alternate gaseous fuels, which can be used in the dual fuel engines. These are:

- Hydrogen [74]
- Natural gas [75]
- Sewage gas [76]

- LPG (Liquified Petroleum Gas) [77]
- Town gas [78]
- Producer gas, [79] etc.

For a gas to be easily combustible in the DF (Dual Fuel) engine, it must be having a minimum C.V. of 4500kJ/Nm^3.

On the basis of the basic engine, from which the dual fuel engine is modified, the dual fuel engines are classified into the following types:

2.3.2 Classification of duel fuel engines:

The basic difference between a diesel and a gasoline engine is that the diesel engine operates on high compression ratio and has an injection system with no spark device where as the gasoline engine operates on low compression ratio and has a carburetor system with a spark device. On this basic difference, there are basically two types of duel fuel engines:

- Dual fuel SI (Spark Ignition) engine.
- Dual fuel CI (Compression Ignition) engine.

2.3.2.1 Dual fuel SI engine:

It is a modification of the basic SI engine in which a gas carburetor is attached to the inlet valve of the SI engine. This gas carburetor has two inlets and an outlet. One of the inlets is connected to the filtered air supply, whereas the other is connected to the gaseous fuel supply. Both the air and the gaseous fuel get mixed in this gas carburetor. In the basic SI engine, where the carburetor is used, the gas and air mixture enters the carburetor and carry with it the required amount of liquid fuel. So now a mixture of air, gaseous fuel and the gasoline enters the SI engine and get ignited near the compression stroke by a spark plug. [80]

In the case of modern SI engine such as EFI engines, MPFI engines, etc. the fuel injection system is not altered, a separate gas carburetor is attached at the inlet of the engine, which provides a homogenous mixture of the air and the gaseous fuel. This mixture then gets laden by gasoline vapors and is easily ignited with the help of the sparking device. [81]

There is another case in which the existing CI engines are modified into SI engines, by replacing the injection device with a spark plug. In such type of engines, the gas carburetor works well by supplying a homogenous mixture of air and the gaseous fuel. These engines can work only on 100% gas fuel without any further modification. If these engines are to be run on dual fuel mode, then certain modification related to the liquid fuel injection need to be made. A carburetor for the liquid fuel can be used just at the inlet of the engine or a fuel injector needs to be installed in the combustion chamber to meet the condition of the dual fuel engine. [82] These engines are better than the SI engines because unlike SI engines, they have a high compression ratio, which makes them more efficient in nature. But, these engines are also associated with a problem of knocking, which arises due to a high compression ratio. [83]

2.3.2.2 Dual fuel CI engines:

A DFCI (Dual fuel CI) engine is a modified CI engine, in which a gas carburetor is installed at the inlet valve of the engine. The homogeneous mixture of the air and the gaseous fuel supplied by the gas carburetor is compressed in the compression stroke and then ignited by the spray of diesel just before the completion of the compression stroke. [84] These engines are quite robust and efficient as compared to the SI engines. There is no problem related to knocking due to the ignition by diesel instead of spark. When the diesel is sprayed inside the combustion chamber, it gets atomized into small molecules. Due to this a large number of flame centers are created, which help in ignition of the gas-air mixture. [85] Unlike compression ignition, the ignition takes place in a different fashion. The combustion takes place in the form of flame propagation and has a fast speed like compression ignition. So it is a mixture of compression and spark ignition. The process is rapid and quite efficient. [86] Due to such a high compression ratio in the DFCI engines and low self ignition temperature of the gases, it is preferred to use a DFCI engine instead of DFSI engine.

There is also a possibility of the modification of the existing modern CI engines such as turbocharged and supercharged engines into DFCI engines. [87,88] As discussed earlier, the gas carburetor is installed before the inlet manifold of the engine. In supercharged or turbocharged engines, the air is compressed by the compressor and sent into the engine via gas carburetor. On the way to the inlet manifold, the compressed gas is enriched with the required gaseous fuel in the gas carburetor. Thus the air-gas mixture is sent into the combustion chamber. This mixture is now ignited with the help of the diesel spray just near the TDC (Top Dead Center). [89]

In the DFCI engines, a problem of air deficiency is faced. [90] Since the volumetric efficiency of the engine is constant, so on the dual fuel mode the engine inhales same quantity of air-gas mixture as initially the air it was inhaling. In other words, less air is supplied to the engine corresponding to the quantity of fuel inside the combustion chamber. Due to this, the performance of the engine goes down and simultaneously increasing the concentration of hydrocarbons in the exhaust. [91,92] To eliminate this drawback, charged engines, i.e. turbocharged and supercharged engines are used to supply a more mass of air inside the combustion chamber. [93] Due to this, corresponding to the same quantity of air supply, more amount of air is supplied to the combustion chamber, thereby increasing the engine performance and reducing the HC emissions. [94]

2.3.3 Performance characteristics of the DF engines:

As it is clear from the above discussion that it is not much difficult to modify an existing engine into a DF engine. Talking about the various performance parameters, it is seen that the dual fuel engines are capable of producing almost the same power output at the dual fuel mode as produced on the conventional/pilot fuel mode. On an average, the dual fuel engines show a decrease in the performance characteristics at lower loads [95]. At lower loads, there prevails a condition of poor mixture strength, which cause the problem of ignition delay. The simultaneous increase in the ignition delays is the main reason for such decrease in the performance characteristics. [96] At high loads, it has been investigated from the previous experimental analysis that the dual fuel engines perform much better than the conventional fuel engines. At higher loads, the charge is distributed evenly throughout the cylinder and the gas particles are occupied in the gaps between the charge particles creating a highly combustible atmosphere. This enhances the combustion efficiency of the engine and the combustion process takes place rapidly, decreasing the chances of incomplete combustion. [97] Considering the overall cases, it is seen that the efficiency of the dual fuel system is almost same as that of the pilot fuel mode. For example, the average efficiency of the engine on pilot fuel mode is 32% the corresponding average efficiency on dual fuel mode is ~28%. [98]

The dual fuel engines are known for the high conventional fuel replacement. [99] In most of the cases it is seen that these engines can replace to maximum of ~80% of the conventional fuel, with a slight reduction in the net power output. Many times these engines are run on 100% gaseous fuel with a smooth operation. Thus, it can be concluded that these engines can run smoothly on all the three modes, i.e. pure pilot fuel mode, pure gaseous fuel mode and dual fuel mode. These engines respond very quickly to the change in the mode of operation. [100]

2.3.4 Emission characteristics of the DF engines:

As far as the emission characteristics are concerned, the DF engines produce relatively low emissions at higher loads as compared to the pilot fuel mode operation. As discussed in the previous section, at higher loads, the pilot fuel and the gaseous fuel particles are well distributed inside the combustion chamber, which get combusted very rapidly, with very less chances of incomplete combustion. So, at the higher loads, the emission of the dual fuel engine are controlled to a great extent, i.e. the concentration of CO, HC, NOx, etc. in the exhaust is found to be very low. [101]

Whereas at lower loads, a different trend is seen. Due to the air deficient atmosphere inside the combustion chamber, there exists a condition of incomplete combustion, due to which a significant concentration of CO and HC is found in the engine exhaust. Unlike CO and HC emissions, NOx emissions as well as the exhaust gas temperature show a decreasing trend due to the fact that incomplete combustion produces less heat inside the combustion chamber so due to low temperature of the combustion chamber, lesser amounts of oxides of nitrogen (NOx) are formed and so is the case for the exhaust gas temperature. The NOx are highly reduced by ~40% to 75% on dual fuel mode. [102]

2.3.5 Advantages of dual fuel engines:

Over the conventional CI engines the duel fuel engines have many advantages. These are listed below:

- Conventional fuel saving by a significant amount.

- Use of gaseous fuel in the combustion restricts the combustion of the lubricating oil and also increases its life, due to relatively low wear and tear in the engine.
- Since gaseous fuels are clean in nature, i.e. they are non polluting, a similar trend is also seen in the case of the dual fuel engines.
- No residue is left behind on any cylinder part or in the exhaust.
- Significant reduction in the CO, HC, NOx and SOx emissions.
- In case of a biogas coupled dual fuel engine, the engine exhaust can be used to provide the heat for the digestion process.
- Due to the highly responsive nature of these systems, the engine can be easily shifted on the diesel/gasoline mode in case of an emergency.

2.4 Noise and its characteristics for DF engines:

Noise refers to an unwanted form of sound, which is quite annoying and disturbing in nature. It is that unwanted noise, which makes it difficult for a person to hear the wanted noise. The noise coming from a heavy machine in an industry, loud and disturbing sound of the loudspeakers used in marriages and other functions, etc. are a few forms of noise, that we experience in the daily life. [103]

2.4.1 Terms in sound analysis:

2.4.1.1 Sound waves:

These are the waves, which are generated due to the pressure variations in a mechanically operated material/device. [104]

2.4.1.2 Sound power:

Since sound is also a form of energy, which is produced due to the pressure variations, so during the transfer of sound, a significant amount of power is also linked. This power is called sound power. Like the electric and mechanical power, it is also measured in watts (W). [104]

2.4.1.3 Sound intensity:

As a result of the production of sound by a source, a sound intensity is also created at some distance, which gives the measurement of the power through certain area upto that distance. In other words, it is defined as the ratio of sound power to the area covered by this sound. [104]

2.4.1.4 Sound pressure level:

It is defined as the logarithmic ratio of the measured sound pressure to the reference sound pressure. It is measured in decibels (dB). [105]

2.4.1.5 Sound intensity level:

It is defined as the logarithmic ratio of the measured sound intensity to the reference sound intensity. Like sound pressure level, it is also measured in decibels (dB). [105]

2.4.1.6 Hearing range:

Hearing range is defined as the range of the frequencies, that can be heard by a normal living organism. The range depends upon the category of the living organism. It can be a human, an animal, a marine organism, etc. For humans, this range lies between 20 Hz to 20 kHz. As a result of lab investigation, it has been found that a normal human can hear sounds with a frequency of 12 Hz to a frequency of 28 kHz. [106]

2.4.1.7 Threshold of hearing:

It is the sound level, having a pressure of 20 µPa. It is the measure of the lower limit of the hearing range. [107]

2.4.1.8 Absolute threshold of hearing:

It is the minimum sound level of a pure tone, i.e. a tone having single frequency, which a normal human being can hear easily, when no other sound/tone is interfering. [108]

2.4.1.9 Threshold of pain:

It is that sound pressure level at which it becomes painful for a normal human to bear this sound. It is called threshold of pain because at this sound level, problems such as hearing impairment, physical damage, etc. are experienced. The value of threshold of pain lies normally above 130 dB. [108]

Table 3 Threshold of pain [108]

Sound Level	**Sound pressure**
120 dB	20 Pa
130 dB	63 Pa
134 dB	100 Pa
137.5 dB	150 Pa
140 dB	200 Pa

2.4.1.10 Noise:

It refers to an unwanted sound, which can be as faint/tinny as the sound coming from someone's headphones or as loud as the roar of a jet engine. [106]

Table 4 Some examples of sources with their respective sound levels. [109]

Source	**Sound power (W)**	**Level (dB)**
Saturn rocket	100,000,000	200
After burning jet engine	100,000	170
Centrifugal fan at 849,000 m^3/hr	100	140
75 piece orchestra, Vane axial fan at 169,900 m^3/hr	10	130
Large chipping hammer	1	120
Blaring radio, centrifugal fan at 22,087m^3/hr	0.1	110
Auto on highway	0.01	100
Food blenders-upper range	0.001	90
Dishwashers-upper range	0.0001	80
Voice-conversational level	0.00001	70
Quiet-Duct silencer, self-noise at +1000 ft/min	0.00000001	40
Voice-very soft whisper	0.000000001	30
Lowest audible sound for persons with excellent hearing	0.000000000001	0

2.4.2 Noise characteristics of a dual fuel engine:

It has been investigated that the combustion parameters such as ignition quality, fuel stability, flow properties, etc. in an IC engine are greatly influenced by the chemical and the physical properties of the fuel. In case of reciprocating engines, there are many sources from which noise is produced. [110] These are:

2.4.2.1 Combustion noise:

The combustion noise is mainly caused due to unsteady and sometimes uneven combustion of the fuel in the combustion chamber. The fluctuation in the frequencies produced by the combustion roar is the main cause of combustion noise. [111] The pressure forces responsible for the combustion noise in the dual fuel engine are dependent on the parameters such as fuel injection system, which is further dependent on the fuel's chemical and physical properties such as cetane number in case of CI systems and octane number in case of SI systems, bulk modulus, viscosity, etc. Apart from the fuel properties, the combustion noise is also influenced by the design of the combustion chamber and it designed geometry. [112]

There are some other reasons of excessive combustion noise. These can be classified as:

- Improper combustion due uneven charge distribution
- Knocking in case of DFCI engines due to sufficiently large ignition delay.
- Detonation in case of DFSI engines due to high compression ratio, overheating of the engine, poor octane rating of the fuel, etc.

2.4.2.2 Exhaust noise:

The exhaust gases are sent into the atmosphere from the engine manifold by a tail pipe. During the scavenging action of the engine, the exhaust gases get compressed. Due this compression, the generated pressure waves produce the sound waves, which come in the form of exhaust noise. [113] In the passage from the engine exhaust manifold to the gas exhaust in the atmosphere, there are present a number of orifices, which compress and decompress the exhaust gases. These orifices contribute to the secondary sources of the exhaust noise. [114]

2.5 Review of previous research work:

Jorapur R., et al.; (1997) manufactured a commercial-scale (1085 MJ h^{-1}) gasification structure using low-density biomass, for thermal applications. Sugarcane leaves and bagasse, sweet sorghum stalks bajra stalks, and bagasse etc were used as fuel in the gasifier. The gas had a CV of 3.57-4.85 MJ/mm^3. The system produced 24wt% char of the original fuel. After testing the system in the laboratory, it was tested at a metallurgical company, where it was modified and fitted to an oil-fired furnace for manufacturing of specialty ceramics. They operated the furnace completely on the gasification system and the output quality was enhanced.

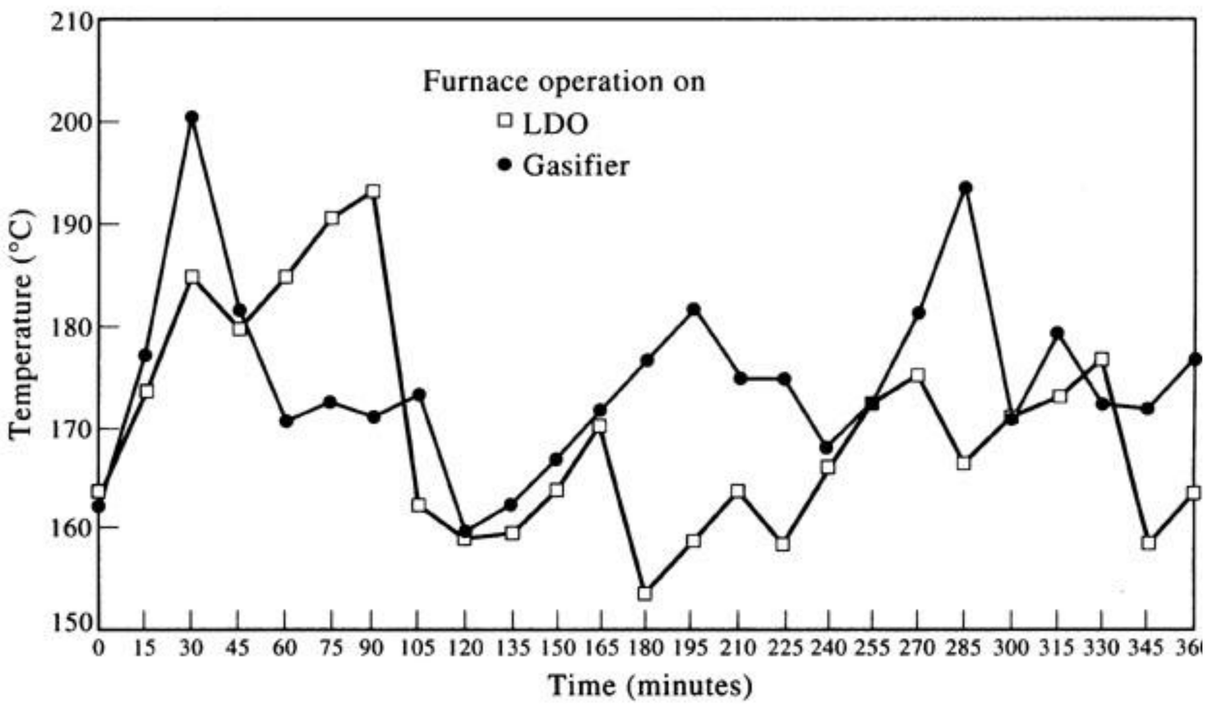

Fig 10 Variation of furnace temperature with time. [115]

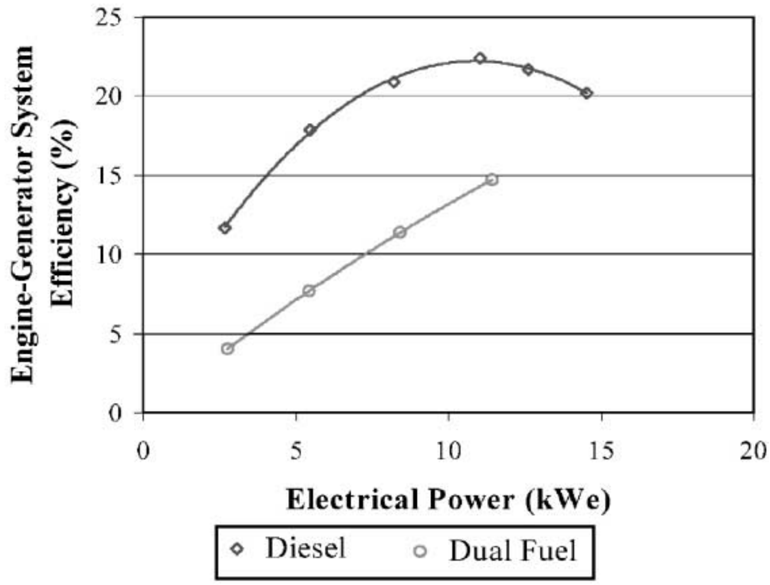

Fig 11 Engine–generator efficiency as a function of electrical power output. [116]

Bhattacharya S.C., et al.; (2001) developed a multi-stage charcoal based biomass-gasification system to synthesize a the gas having low tar characteristics for a DF engine application by gasifying coconut shells. The gasifier-engine system consisted of a charcoal based biomass–gasifier, a gas cleaning, and cooling unit and a modified diesel engine.

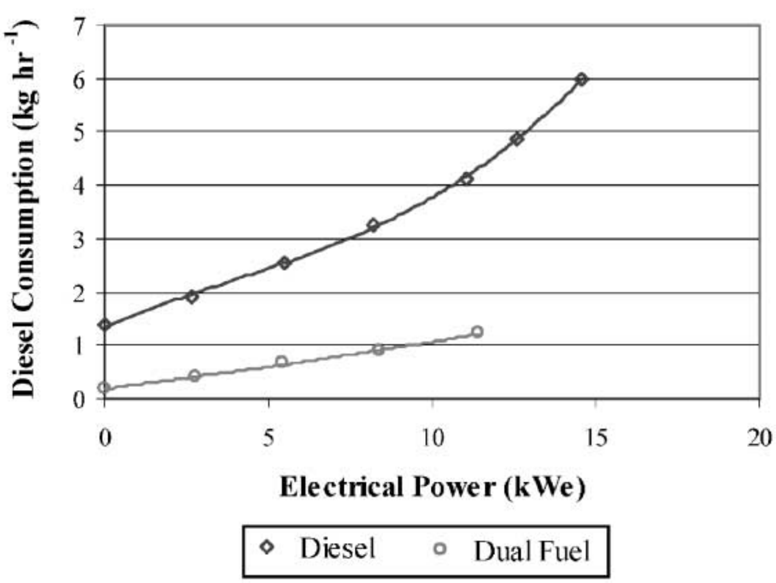

Fig 12 Diesel consumption as a function of electrical power output. [116]

The tar found in the gasification of the coconut shells was 29 mg/Nm^3. The producer gas was cooled down to 42°C. A tar-free gas was supplied to the engine, before cooling the gas from the gasifier system. A modified engine having 3 cylinders was tested on dual fuel mode. It was run at a constant speed of 1500 rpm on diesel and dual fuel modes. The dual fuel mode operation was able to replace a maximum of 81% of the total energy input. An electricity generation of 11.44 kW was also reported.

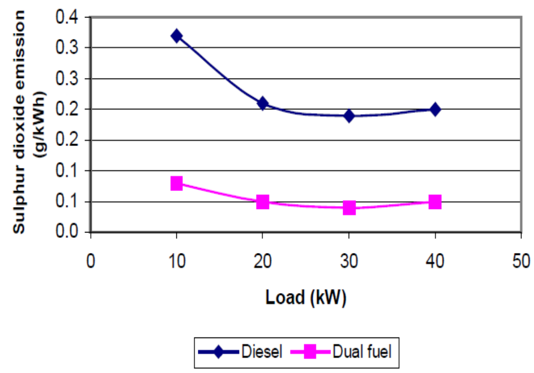

Fig 13 Sulphur dioxide emission from engine operated on diesel and dual fuel mode. [117]

R.Uma, et al.; (2004) investigated the emission characteristics of a diesel engine at different load conditions in diesel alone and dual mode (with producer gas).

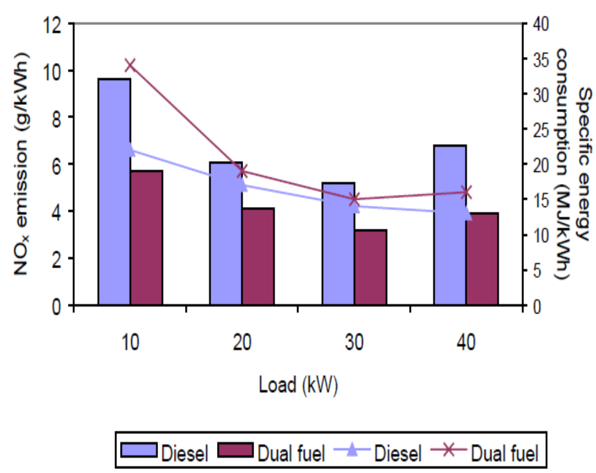

Fig 14 Comparison of NOx emission from diesel engine in diesel alone and dual fuel mode. [117]

In the reported work, the pollutants NOx, HC, CO, SOx, and particulate matter in the flue gas were studied for their various characteristics on the dual fuel mode and compared with the pilot fuel mode. Apart from the emission characteristics, the engine was also investigated for the estimation of average diesel replacement on the dual fuel mode. At lower loads, the engine was observed to be emitting a greater concentrations NOx and SOx. On the dual fuel mode, there is a significant increase in the CO and HC concentrations at all load conditions. Whereas NOx and SOx emissions are found to be decreasing on the dual fuel mode at higher loads. A significant increase in the pilot fuel replacement is also reported.

Sridhar G, et al.; (2005) designed and fabricated dual fuel engine. An, ultra clean, low energy density and high octane rating producer gas derived by the gasification of biomass was analysed. The design was developed in order to study the effect of ignition timing and compression on the net power output of the engine. The design aspects were studied properly and applied to the commercially available engines of two different make. A producer gas carburetor was also developed to send the gaseous fuel into the cylinder. On an average, there was a loss of 20-30% in the net power output of the engine when operated on dual fuel mode. On dual fuel mode this loss was compensated by a large reduction in the emission of the engine. It was reported that the engine emitted very less quantities of NOx and almost zero SOx.

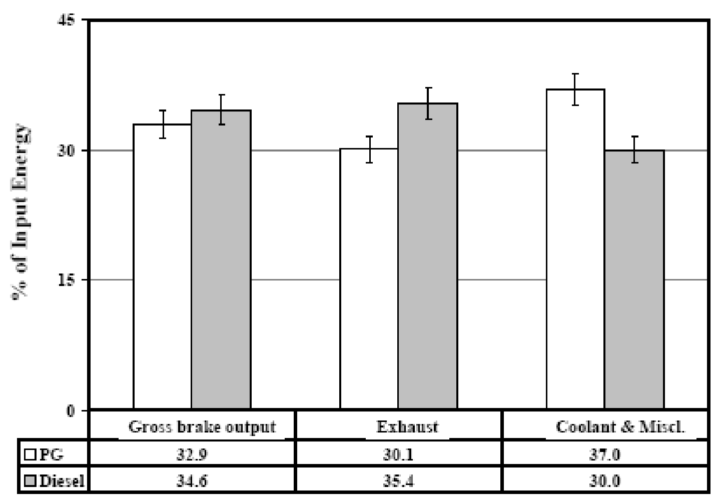

Fig 15 Energy balance comparison in diesel and producer gas mode at maximum brake output.

[118]

Sridhar G, et al.; (2005) analysed practically the emission measurements comprising of CO and NOx on a DFCI engine and a spark type gas engine. Blends of diesel and synthesis gas were used as a fuel in case of DFCI engine. Whereas 100% ultra clean synthesis gas was used in spark type engine. Due to lower maximum flame temperature, the NOx concentration was found to be lower as compared to the pilot fuel mode. Whereas, due to incomplete combustion, the CO levels were higher. The air deficiency was the main reason for such an issue of incomplete combustion. NOx and CO levels were observed to be much lower in the case of the gas alone operated spark engine. In comparison to the existing emission norms, these levels were much lower and the engine showed a smooth and sustained operation.

Ramadhas A.S., et al.; (2006) used a "Canon" make downdraft gasifier for the production of producer gas and it was coupled to a "Canon" make four stroke direct injection engine setup. The engine produced a rated power output of 5.5kW at full load and 1500 RPM.

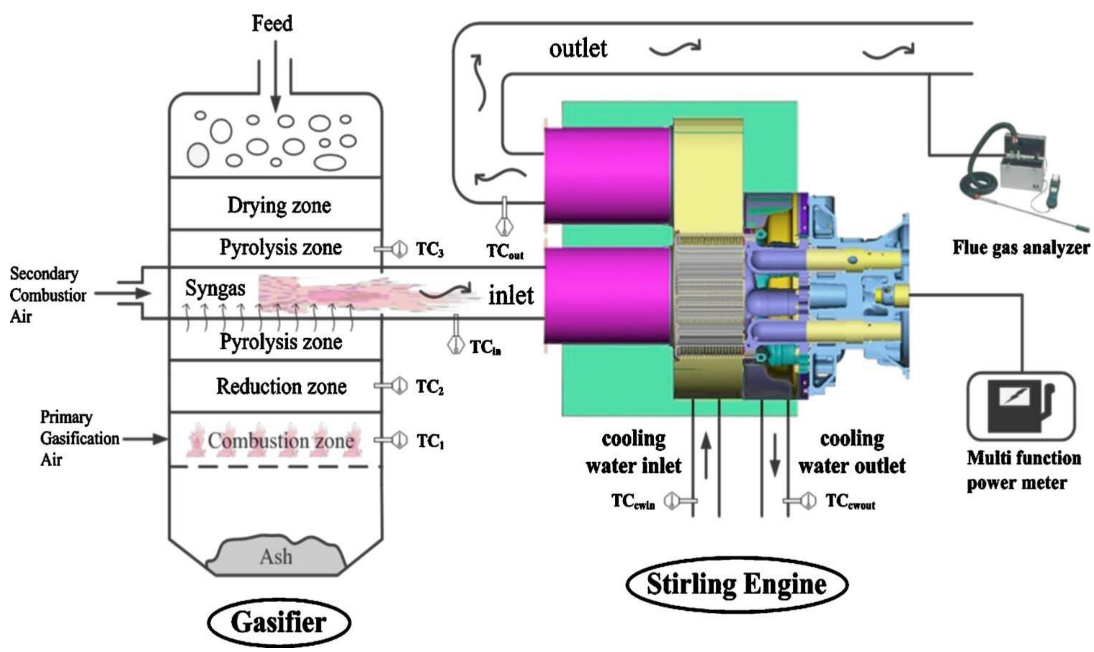

Fig 16 The schematic of the updraft gasifier coupled with a Stirling engine [121]

Wood chips and coir pith were used separately to produce the producer gas. The dual fuel engine was tested on pilot fuel mode as well as on dual fuel mode for both emission and performance characteristics using both the samples of the gas separately. It was found that at lower load values, the performance of the engine in terms of power output got lowered and the emissions of the engine also increased. Whereas at higher loads, the performance and emission characteristics were almost same. At all load values, in dual fuel mode, the CO emissions were higher than that of diesel mode. There was a significant reduction in the consumption of conventional fuel, i.e. diesel in the blends of both the gas samples, but it was noted that the fuel replacement is more in case of the gas produced from the wood chips as compared to the coir pith reason being the higher CV of the gas produced from the wood chips.

Lin J.; (2007) investigated a fixed bed updraft gasifier system by feeding the gasifier with carpentry waste. This system was further coupled to a Stirling engine to produce a significant electrical output b the virtue of the electrical generator coupled to it. The schematic diagram is shown in the Fig 14. The data acquisition system and the exhaust gas analyser were also coupled to get a record of various performance characteristics of the engine. It was recorded that the flue gas, which fire the stirling engine at their entrance contain a total of 95kW of thermal energy, out of which, the engine was able to convert only 26%, i.e. 25 kW of the total energy. Net electrical output was 24.5 kW. The fraction 0.5kW was lost in 400V/220V step down operation in the transformer.

Papagiannakis R.G., et al.; (2007) developed a mathematical model for the investigation of performance and emission characteristics of a spark ignition engine. The model was the basis for those engines, in which the load on the engine is controlled by the respective variation in the air fuel ratio and the amount of gaseous fuel intake. This model was developed to predict the trends of various performance and emission characteristics. These results were further compared with a lab scale, fully developed and functional spark ignition engine. This engine was tested for both performance and noise characteristics. On comparing the results of both the model prediction and the experimental setup, it was concluded that the results coincide to a great extent. The NOx emissions of the engine followed almost the similar trend as the predicted value. Whereas it was seen that the CO emission tended to deviate from the predicted value. The engine was also tested on natural gas in order to compare the results with the syngas fuel. In almost all the aspects, such as brake power, brake specific fuel consumption, NOx emissions, CO emissions, etc., natural gas proved to be a better gaseous fuel as compared to syngas.

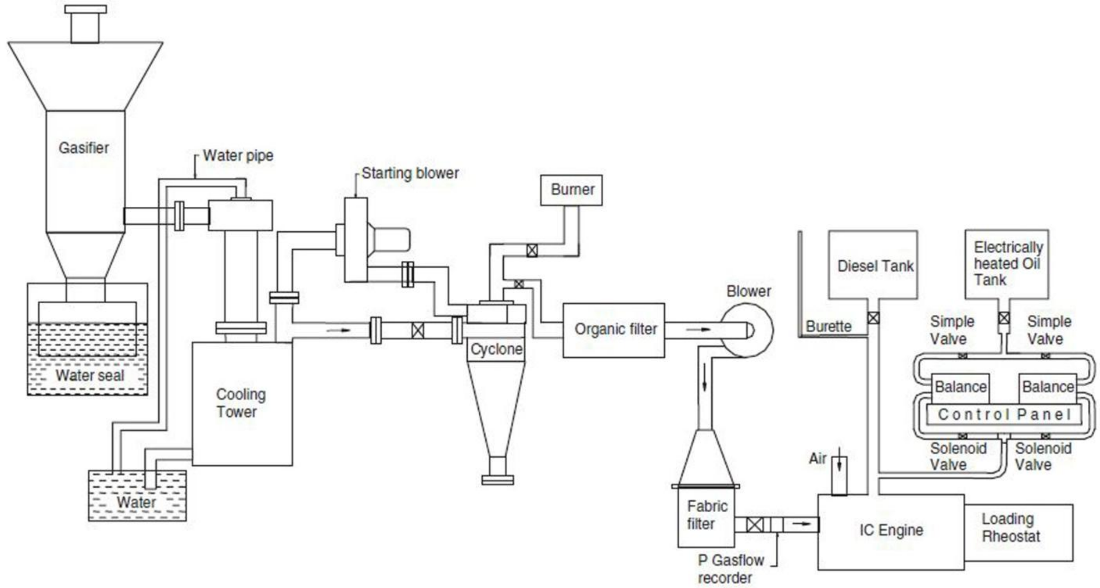

Fig 17 Schematic diagram of the gasifier-engine setup with accessories [123]

Singh R. N., et al.; (2007) used a new engine of Kirloskar make, which produced 23kW at 1500RPM. This engine was modified to a dual fuel engine by fitting a gas carburetor at the inlet manifold. Usually this engine had a maximum compression ratio of 17:1.But this ratio was further increased to 19.4:1 using a centrifugal compressor, which sent compressed air inside the engine cylinder. The engine was operated on mainly four different modes: diesel mode, rice bran oil+diesel mode, diesel+producer gas mode and the mixed fuel mode, which consisted of all the three fuels. The schematic diagram is shown in fig 15. On these modes, the engine was tested for performance and emission characteristics. It was concluded from the experimental observations that at 84% load, the diesel and producer gas mode generated maximum amount of HC emissions, the reason being the incomplete combustion due to lack of air/oxygen. At all load values, the CO_2 emissions were maximum in case of mixed fuel mode, which ensured a maximum combustion efficiency. The CO and the NOx emissions were suppressed to a great extent in diesel-gas mode as well as the mixed fuel mode at higher loads.

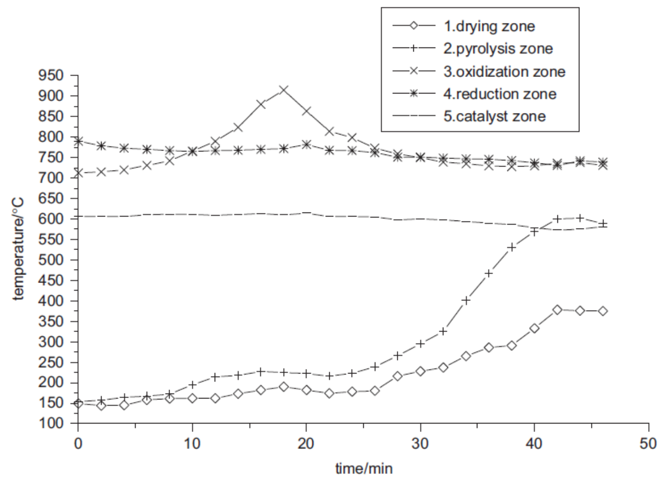

Fig 18 Temperature profile along the height of downdraft gasifier. [124]

Pengmei L.V., et al.; (2007) developed a system, which was capable of producing hydrogen rich producer gas. The gasifier was such designed that it was able to heat itself without any external source and char played the role of a catalyst. The performance of the system was estimated from the temperatures of various zones like pyrolysis zone, combustion zone and reduction zone. The temperature of the neck was found to increase with the feeding rate for similar ER values. For increasing the production capacity, accelerating the feed rate is essential. But it was later on concluded that the high feeding rate results in an in the yield of the gas and a significant reduction in the residence of the gas, thus results in degradation of the quality. There is an increase in the temperature with an increase in the feeding rate, but the yield of hydrogen decreases with feeding rate.

On successful working of a 125 kg/h down draft biomass gasifier, **Pathak, B. S., et al.** in **2008** developed an upscale version of the existing biomass gasifier, which had a capacity of 375 kg/h of biomass conversion. This system was tested for its performance characteristics. This gasifier system was operated using two different kinds of fuels: biomass briquettes and babool wood. The briquettes were composed of 60% de-oiled caster oil cakes and 40% sawdust. The operation of the gasifier on briquettes fuel generated a gas flow rate of 278 Nm^3/h at a biomass consumption rate of 122 kg/h. The cold gas efficiency of the process was 70%. When the gasifier was operated using babool wood, a gas flow rate of 460 Nm3/h was reported, which produced by 181 kg/h consumption of babool wood. This process had a cold gas efficiency of 71%. The average heating value of the gas was ~5.2MJ/Nm^3. Apart from this, a gas burner to burn the produced gas was also designed. This burner was a jet type burner, with three air inlets. Due to these air inlets, the burner was able to inhale 10%-25% air, so due to this, a separate air blower was not required. The schematic diagram of the experimental setup is shown below in Fig 17.

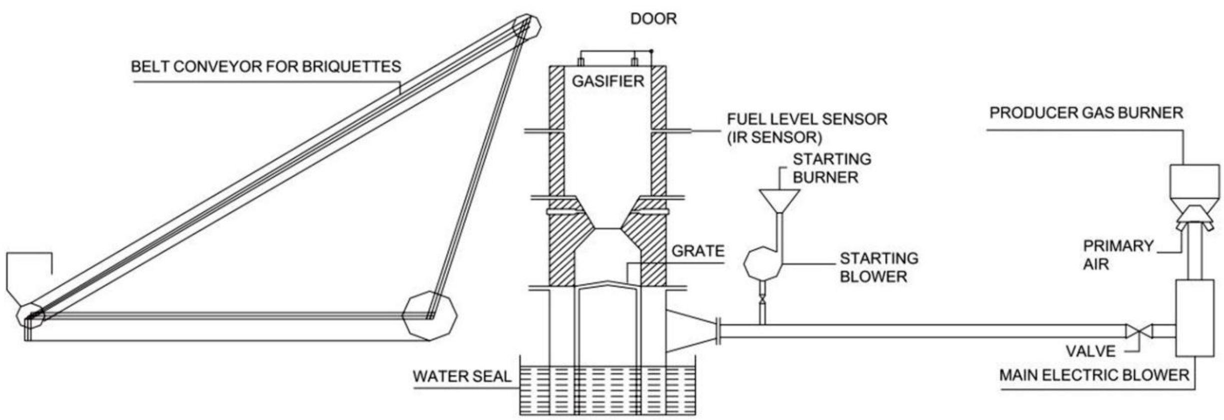

Fig 19 Schematic diagram of the experimental setup including the conveyor system. [125]

Ramadhas A.S., et al.; (2008) used a “Canon” make downdraft gasifier for the production of producer gas and it was coupled to a “Canon” make four stroke direct injection engine setup. The engine produced a rated power output of 5.5kW at full load and 1500 RPM. Coir pith was used to produce the producer gas. Apart from this, rubber seed oil was also fired alone as well as by blending it with the diesel and producer gas. The dual fuel engine was tested on four different modes, i.e. oil and producer gas mode, diesel and producer gas mode, diesel mode and oil mode for both emission and performance characteristics. From the experimental results, it was concluded that the engine showed a decreased performance in terms of brake power when operated on dual fuel mode using oil-gas blends and diesel-gas blends. Due to lower CV of the rubber seed oil, the results show a greater consumption of oil as compared to diesel when both are operated on the pilot fuel mode. The oil-gas mode results in an increased CO emissions as compared to any other mode. The other emissions in all the modes follow a similar and same trend and the results are quite close to each other.

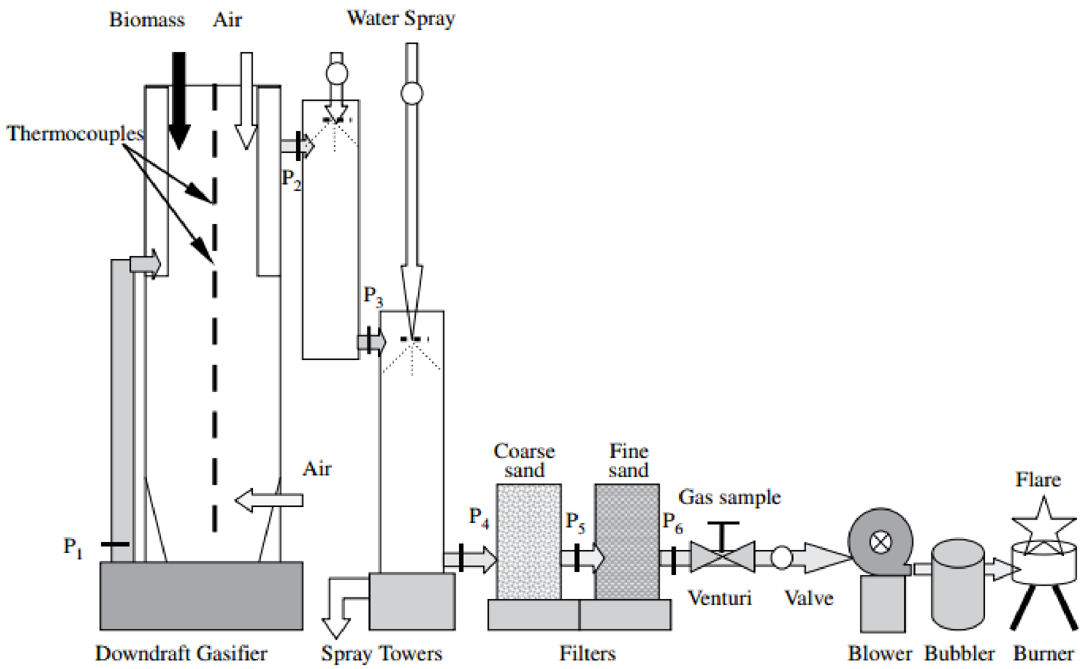

Fig 20 Schematic diagram of the 75 kW downdraft (biomass) gasifier system [127]

An experimental investigation was carried by **Sharma A K.,** in **2009** to study a downdraft biomass gasifier system. It had a rated power output of 75 kW. Various characteristics such as temperature profile, gas composition, CV etc.were studied. Apart from these, trends for pressure drop across the porous gasifier bed were obtained by analysisng the system in both non-firing as well as firing mode. The biomass flowed due to gravity and air was injected using a blower. The experimental setup was designed to get the various flow characteristics of the gasifier and to get the trend for temperature variation in the reactive bed, CV and the gas composition. In case of non-firing mode, a greater pressure drop was noticed in the extinguished bed in comparison to the freshly ignited bed. Where as in case of firing mode, a higher bed temperature was obtained, which helped in better conversion of incombustible constituents in the produced gas thereby improved the CV of the resulting gas.

Shah A., et al.; 2010 assembled a biomass gasifier system, capable of supplying a constant stream of syngas and a 5.5 kW spark ignited four stroke single cylinder reciprocating engine. This system was capable of running at 100% gas mode. There was a significant reduction in the power output of the electric generator. On gas mode, the maximum power output was 1342W of electric power. Whereas a gasoline mode, maximum electric power output was 2451W. The maximum overall efficiency in both cases was same and 19.3%. This engine was also tested for emission characteristics at different load values. The CO emissions showed a significant reduction of around 80% on the syngas mode operation. The CO emissions show an increasing trend with the increase in the load value. In case of CO_2 emissions, an increasing trend of values was reported. The emission on gas mode were higher as compared to the gasoline mode due the increased source of CO_2 in syngas gas mode. In syngas mode, CO_2 is generated from the complete combustion of CO in the combustion chamber of the IC engine as well as the producer gas also contains a significant amount of CO_2 resulting from the complete combustion of biomass in the gasifier system. The NOx and the HC emissions were significantly decreased in case of syngas mode operation.

Coronado C. R., et al.; 2011 developed a down draft gasifier cogeneration system, which was capable of supplying electricity, hot water and cold water. The schematic diagram for the generation of hot water is shown in fig 21. The cold water is first used to cool the lubricating oil, then it is allowed to cool the engine by passing through water jacket and finally it is used to cool the exhaust gases and gets converted into steam/hot water, depending upon the engine operating time

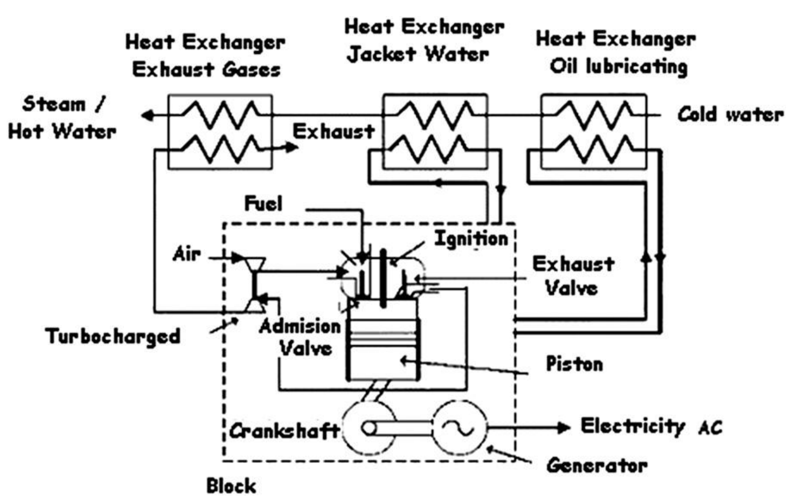

Fig 21 Schematic diagram showing the positions of the fitted heat exchangers for hot water supply [129]

The gasifier was run using wood fuel to produce the gas. They presented a good analysis of the first law of thermodynamics for the co-generation system. They achieved a global efficiency of 51.42%. The electricity generation system had an efficiency of 21%. Whereas the hot water generation system had an efficiency of 24%. The cold water or the refrigeration system had a quite low efficiency of only 5.7%. Apart from the experimental analysis, the cost analysis of the system was also reported in the study.

Son Y. I., et al.; 2011 also developed a downdraft biomass gasifier system, which was capable of gasifying biomass at a rate 40-45 kg/hr. The raw material used for the analysis was wood chips. The raw material was fed with the help of a belt conveyor. The temperature of the combustion and the gasification or the reduction zone was fixed at ~1000^{o}C. The best gas at a flow rate of ~100 Nm^3/h with a heating value of ~5000 kJ/Nm^3 was obtained at an equivalence ratio of 0.34. Since the gas was to be used in an IC engine system, then it needed some initial cooling and proper cleaning. For this a separate tar removal unit was also developed. This unit was capable of removing high values of tar contents. But, in the present study, very small amount of tar was generated and it was removed simultaneously. This system was coupled to a spark ignition 3 cylinder engine-genset, generating 10 kW of electric power. This engine was otherwise operated on LPG. The engine was tested for its performance and emission characteristics. These results were further compared to the results of the engine when operated on LPG fuel. It was reported that the HC emission were less than 200 ppm whereas the NOx emissions were limited to only 40 ppm.

Erlich C., et al.; 2011 developed a downdraft gasifier system, which was designed to gasify almost any kind of dry fuel by its densification in other words by making its pellets. The sugarcane bagasse, wood and the empty fruit bunch (EFB) were used as biomass raw materials. The pellets of these materials were produced from their pulverized form in a pellet mill model - CL3 with a maximum capacity of 20 kg/h. Four types of pellets were made wood pellets of 6mm diameter, sugarcane bagasse pellets of 6mm diameter, EFB pellets of 6mm diameter and EFB pellets of 8mm diameter.

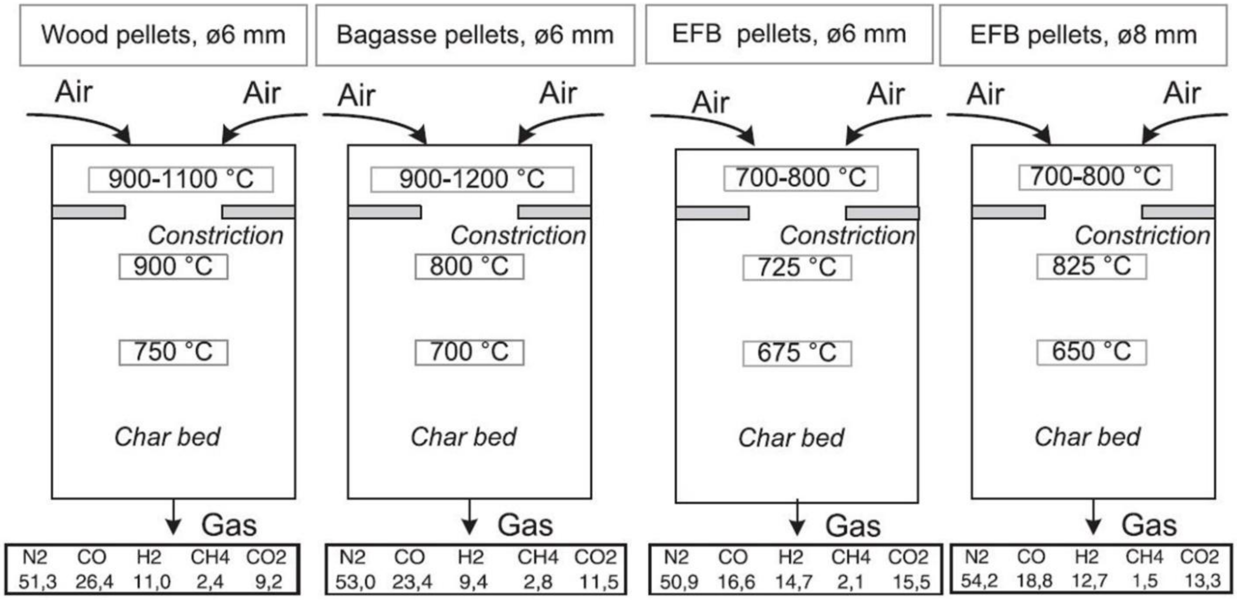

Fig 22 Diagram depicting the information of the gasification of the four different fuel pellets along with temperature and gas composition information [131]

A maximum cold gas efficiency of 76% was obtained in the case of wood pellets. The biomass consumption rate ranged from 2 – 3.2 kg/h and corresponding gas flow rate of 4.8 – 6.8 Nm^3/h was obtained. The following figure shows a schematic representation of temperature characteristics of various biomass pellets along with the characteristic producer gas composition.

Jaojaruek K., et al.; 2011 developed a downdraft gasifier, with an important improvement in the gasification system. In this new system, the gasification process was carried out in two stages. So this system was called as two stage gasification system. In this process, usually the air is supplied at primary and secondary positions. The primary position is the combustion zone and the secondary position is the pyrolysis zone. In the previously developed two stage gasification system, air was supplied at both the positions, but in the current study, air is supplied only at primary position, whereas pre-mixed air and producer gas are supplied at the secondary positions. This system resulted in the enhancement of the CV of the gas, production rate of the gas and the reduction in the tar generation. The gasifier was operated on three modes: single stage gasification (SS), two stage gasification with air at both positions (AA) and two stage gasification with pre-mixed air and gas at the secondary position (AG). The performance characteristics of all these modes were compared with each other. It was concluded that the SS process produces maximum tar ~1.28 g/Nm^3 and minimum percentage of combustible gas ~28%, whereas it is inverse in the case of the AG process, it produces minimum tar ~43.2 mg/Nm^3 and maximum percentage of combustible gas ~43%. The CV of the gas rose to 6.53MJ/Nm^3.

Olgun H., et al.; 2011 designed and fabricated a downdraft draft biomass gasifier system coupled to a gas cleaning and cooling system. The new and novel improvement in the design was the introduction of the concept of the throat in the gasifier system. As a result of this new concept, there was a significant reduction in the tar contents of the producer gas. The CV of the gas was also increased relatively. During the operation, there was no issue related to the blockage due to tar, ash fusion, etc. The gasifier system was operated using wood waste, barks, hazelnut remains, olive pulp remains, etc. At the equivalence ratio of 0.35, the producer gas of highest CV was obtained. The highest CV of the gas was 5.5 MJ/Nm^3.

Martínez J D, et al.; (2012) analyzed the significance of air in the process of gasification of biomass in downdraft gasifiers. The experiments showed that the equivalence ratio should range from 0.2 to 0.4.1. Whereas the size of the particles should not be more than 6 cm and the less than 24% moisture should be present. The CV of the gas and the cold gas efficiency of the process were 5-6 MJ/Nm^3 and 55-75% respectively. The combustion zone had a mean temperature of ~1000^{o}C. Due to the low C.V. of the gas, there was a decrease in the volumetric efficiency and the power output of the engine. Due to high speed of the flame in case of dual fuel mode, the spark was retarded, and later it was sustained due to the hydrogen in the mixture. Since air was used as an oxidizing agent, so around 40-55% of nitrogen was observed in the producer gas. In the case of dual fuel mode, the nitrogen played an important role to suppress the knocks, this benefited in those cases where high compression ratio engines are used.

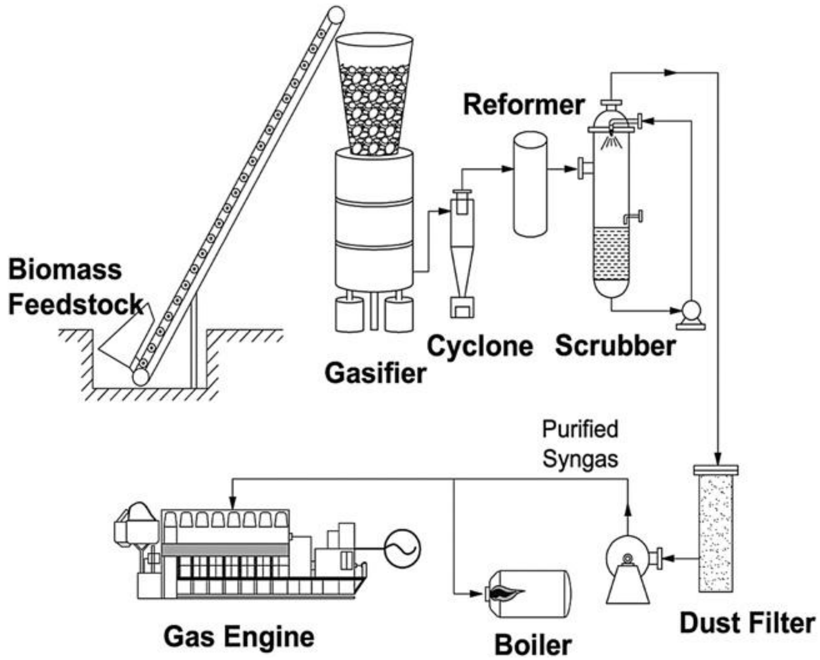

Fig 23 Schematic diagram of the gasifier-gas engine system along with the gas cleaning unit [135]

Yoon S. J., et al.; (2012) developed a downdraft gasifier for the gasification of biomass. They used rice husk and rice husk pellets as raw materials for the analysis. The fuel/raw material was gasified at a temperature range of 600-850^{o}C at an equivalence ratio of 0.45-0.6 in the case of rice husk and 0.2-0.32 in case of rice husk pellets. The rice husk synthesized a gas with a CV of 4518.72 kJ/kg. Whereas in case of rice husk pellets, the producer gas had a CV of 5497.77 kJ/kg. This gasifier system was coupled to an IC engine setup. The schematic diagram is shown as above in fig 23. This engine was initially operated on LPG. The use of this gas in an LPG operated CD800L engine, generated a maximum of 10kW of electric power at 3600RPM of the engine. The cold gas efficiency in the rice husk mode and the rice husk pellets mode was 60% and 70% respectively.

Centeno F., et al.; (2012) made a mathematical model to check the performance of a fixed bed downdraft gasifier coupled to an IC engine setup. For this two separate models for both the gasifier as well as the spark ignition IC engine were made. The gasifier model consisted by dividing the gasifier into 3 subparts, i.e. drying and pyrolysis zone, combustion zone and reduction zone. Different types of kinetics were used for the analysis. The model as well as the experimental setup were tested for the performance analysis. Finally the results of the developed model were compared with some other already developed models as well as with the present results of the experimental setup. It was concluded from the theoretical as well as the experimental results that the developed model showed the composition of the gas as 23% CO, 12% H_2, 8% CO_2, 56% N_2, ~1% CH_4. From the experimental results, it was reported that the engine produced a maximum of 16kW of indicated power at 3600RPM.

D.K. Das, et al.; (2012) modified a single cylinder, four stroke diesel engine, generating a power output of 5.3 kW. The performance of this diesel engine was studied in terms of its thermal efficiency, SFC and diesel substitution on diesel alone and dual fuel mode. Three types of biomass materials were used, these were wood chips, pea stalks and corncobs. The producer gas system consisted of a downdraft gasifier, a cleaning and cooling followed by a filter unit. A gas air mixing carburetor was designed to inject the gas air mixture in to the 5.3 kW diesel engine on dual fuel mode. The moisture in the biomass was varied from 8- 21%, engine speed as 1550 rev/min and with loads were varied to report the corresponding performance of the engine. There was a slight decrease in the average thermal efficiency on dual fuel mode as compared to the diesel mode. There was a reduction of 60-64% specific diesel consumption in dual fuel mode than that in diesel mode for the same amount of energy output. The average diesel substitution of 74%, 78%, 82% was reported for wood chips, corn cobs and pea stalks respectively.

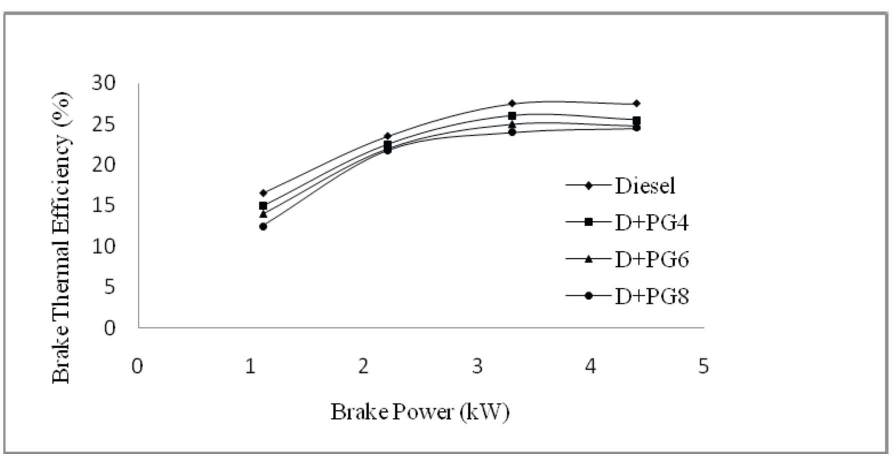

Fig 24 Effect of brake power on brake thermal efficiency in dual fuel mode [138]

Shrivastava V, et al.; (2013) designed and developed a downdraft gasifier to use wood chips and mustard oil cakes in the ratio of 7:3 as a feedstock. An experimental investigation was also carried out to evaluate the performance and emission parameters of a single cylinder, four stroke, air cooled engine developing power of 4.4 kW at a rated speed of 1500 rpm running on a dual fuel mode. In this mode, the producer gas was introduced in the inlet manifold of the engine at a flow rate of 4l/m, 6l/m and 8l/m respectively while diesel was injected into the engine as the main fuel. The results obtained from the dual fuel mode were compared with standard diesel operation. Results indicated that a reduction in the consumption of diesel was observed when operated on dual fuel mode, though there was a reduction in brake thermal efficiency. The nitrous oxide emission was found to be very low in dual fuel which is a great advantage of dual fuel mode over diesel alone but, carbon monoxide and hydrocarbon emission for dual fuel mode was found to be higher than diesel.

Homdoung, N., et al.; 2014 modified an existing single cylinder naturally aspirated diesel engine to a spark ignition (SI) engine. The experimental setup also included a downdraft charcoal gasifier, which produced gas at a flow rate of 27 Nm^3/h. The gas cleaning and cooling units were also attached next to the gasification system in order to make it clean and cool enough to be used in the modified SI engine. The producer gas alone, produced from charcoal was used as fuel for this engine. In the present study, emphasis was laid on the investigation of the appropriate ignition timing of the gaseous fuel in order to produce the highest and a sustained power output at the corresponding engine speed. The ignition timing of the engine was designed in order to maximize the braking torque of the engine. From the experimental investigation, it was concluded that the ignition timing was proportional to the engine speed, i.e. the ignition timing needed to be advanced with the respective increase in the engine speed. At lower speeds ~1100 RPM, the optimum injection timing was recorded between 21-25^o BTDC. At medium engine speeds ~1500 RPM, the optimum injection timing was recorded between 33 to 38^o BTDC, but at high speeds ~1900 RPM, the optimum injection timing was recorded between 40 to 45^o BTDC. At 1700 RPM, the minimum specific fuel consumption of 0.93 kg/kWh was observed with a brake thermal efficiency of ~19% on full load.

Table 5 Literature review

REF. (YEAR)	INVESTIGATION	MATERIAL / FUEL USED	KEY RESULT	ADVANTAGES	DISADVANTAGES	REMARKS
[115] **(1997)**	Gasifiers for industrial heating applications	Sugarcane bagasse Bajra stalks Sweet sorghum stalks	• An output of 1080 MJ/h was obtained. • Gas has a HHV of 3.56-4.82 MJ/Nm^3	• The product quality of the metallurgic industry improved on producer gas operation	• High tar content in the gas	The product quality improved yet due to high tar content, the gas was unsuitable to be fired in an IC engine
[116] **(2001)**	Multi-stage hybrid gasifier-engine system	Coconut shell	• Low tar content 28mg/Nm^3. • Electricity generation efficiency of 15%	• Low diesel consumption and a significant diesel replacement	• Relatively low efficiency of the system due to low CV of the gas as compared to the conventional fuel.	In spite of low efficiency, the system was capable of generating power from almost a waste.
[117] **(2004)**	Emission characteristics of a dual fuel engine	Wood Briquettes of saw dust Briquettes of crop residues	• At lower loads, due to incomplete combustion, the pollutant concentration in the exhaust increase.	• NOx and SO_2 emissions decrease in dual fuel mode.	• Due to air deficiency, there is an incomplete combustion and thereby an increase in the emission of CO.	It was seen that the NOx emission decrease due to low engine temperature, but at the same time time CO emissions also increase, which need to be controlled.
[118] **(2005)**	Design/modification of existing engines to make them dual fuel/producer gas engines	Causurina wood Coconut shells	• Design/Fabrication of actual CI and SI engines, capable of running on producer gas.	• The higher octane rating and ultra clean nature of gas resulted in low NOx and almost zero SOx emissions.	• Due to low energy density of the gas, there was a decrease in power output of the engine.	Presented experiments were conducted at bench scale, but at large scale, the loss of power output is compensated by low exhaust emissions.
[119] **(2005)**	Exhaust emissions of reciprocating engines using producer gas as fuel	Causurina wood Coconut shells	• Actual testing of the SI and CI engines for the emission characteristics	• Very less NOx emission and almost zero SOx emission.	• CO levels were high due to combustion inefficiencies.	The CO levels were significantly increased, but they were much lower than the emission norms.

REF. (YEAR)	INVESTIGATION	MATERIAL / FUEL USED	KEY RESULT	ADVANTAGES	DISADVANTAGES	REMARKS
[120] **(2006)**	Electric power generation in diesel engines using producer gas as a secondary fuel	Coir-pith and wood waste	• 5.5kW of brake power was developed at 1500RPM in a modified CI engine. • More fuel replacement in the case of wood derived gas	• Significant reduction in the conventional fuel consumption.	• No improvement in the emission properties. • Poor emission characteristics at lower loads whereas almost same emission characteristics at higher loads.	Due to less developed system, it was seen that there was an insignificant improvement in the emission characteristics rather it was deteriorated.
[121] **(2007)**	A stirling engine fired with 100% producer gas and significant electric power generation	Carpentry waste	• 24.5kW of electric power was generated by the engine.	• A significant amount of electric power was generated from waste materials with controlled emission characteristics.	• Out of 95kW of thermal energy of the flue gases, only 25 kW was successfully converted into electric power causing a case of high irreversibility.	It was a good attempt of conversion of waste into electricity, but the thermal systems needed improvement to increase the process efficiency.
[122] **(2007)**	Performance and emission characteristics of a producer gas fired SI engine.	Not reported	• A mathematical "two-zone" model of the dual fuel engine was developed. • The theoretical results were compared with the results of the existing engine setup	• The model was successful in predicting the nature of the performance and emission characteristics of the engine	• There was a deviation in the trends followed by the CO emissions from the predicted value.	This technique is a better way to observe the experiments that take place anyways and the results of the current study were quite acceptable.
[123] **(2007)**	Performance and emission characteristics of a CI engine fired with blends of diesel, rice bran oil and producer gas	Rice bran oil & diesel Diesel & producer gas Mixed fuel containing all the three	• 23kW of power was produced at 1500RPM • Maximum CO_2 emissions in case of mixed fuel mode	• At higher loads, NOx and CO emission diminished to a great extent on diesel-gas mode and mixed fuel mode.	• The diesel-gas mode generated maximum amount of HC emissions at 84% load due to deficiency of air/oxygen	To eliminate the issue of air deficiency, and to increase the volumetric efficiency, compressed air was injected and it helped in reducing CO emissions.

REF. (YEAR)	INVESTIGATION	MATERIAL / FUEL USED	KEY RESULT	ADVANTAGES	DISADVANTAGES	REMARKS
[124] **(2007)**	Hydrogen-rich gas production from biomass materials.	Pine wood blocks	• The maximum CV of fuel gas was 11.11 MJ/Nm^3 • The maximum H_2 yield was 45.16 g/kg of biomass	• Effective, relatively low energy consumption technology	• Chances of poisoning of the expensive catalyst.	In the present study, catalyst was used, but due to tar contents in the gas, the catalyst gets poisoned and then it needs a replacement.
[125] **(2008)**	Performance investigation of a throat type gasifier for its thermal applications	Briquettes of 60% de-oiled caster oil cakes and 40% sawdust.	• An upscale version of 375 kg/h was developed. • A gas flow rate of 278 Nm^3/h at a biomass consumption rate of 122 kg/h was obtained.	• The system was capable of generating a higher CV gas with low tar contents at high flow rate.	• The system had a low cold gas efficiency	The tar contents in the gas were less than the expected value, but they were high enough that the gas was not suitable for operation in an IC engine.
[126] **(2008)**	Performance characteristics of a diesel engine operated on dual fuel mode using non conventional fuels	Rubber seed oil and producer gas derived from coir-pith	• The engine was operated at four different modes using diesel, rubber seed oil and their combination with the coir pith derived producer gas	• Reduction in the NOx levels	• There was a reduction in the performance and emission characteristics of the engine	Due to low CV of the rubber seed oil, the oil consumption was quite high as compared to diesel and the incomplete combustion enhanced CO emissions.
[127] **(2009)**	Experimental study on 75 kW downdraft (biomass) gasifier system	Kiker wood	• Maximum C.V. of 4.1 MJ/m^3 is obtained. • The thermal output of the gasifier was 75kW.	• Ultra clean gas supply due to re-fabrication of the filtering systems or the filters.	• Chances of the fusion of the filter material	In spite of wood chips and charcoal powder, sand was used to filter the gas which has a risk of fusion at a high temperature

REF. (YEAR)	INVESTIGATION	MATERIAL / FUEL USED	KEY RESULT	ADVANTAGES	DISADVANTAGES	REMARKS
[128] **(2010)**	Performance characteristics of the engine and the generation system along with emission characteristics of the engine.	Carpentry waste	• Fluctuating 1342 W of electric power generation • Same overall efficiency of 19.3 was obtained in both the modes	• Significant reduction in the CO emission using 80% producer gas	• Still higher emissions as compared to the gasoline mode operation	As compared to the gasoline mode, there was significant reduction in the electric power output of the system.
[129] **(2011)**	Co-generation of electricity, hot and cold water from a biomass based gasification system	Wood	• Simultaneous generation of hot water, electricity and cold water from a gasifier-engine system	• Better use of the thermal heat energy rejected by the engine	• Low efficiency of the refrigeration system	It was a good combination of different processes operated on a single system with a significant output.
[130] **(2011)**	Gasification characteristics of a downdraft gasification system	Wood chips	• Gasification carried out at ~1000°C • Max flow rate and CV of the gas were 100 Nm^3/h and 5000 kJ/Nm^3 respectively	• Tar free, higher CV and high flow rate gas was produced. • Suitable for firing in both furnaces and IC engines	• Small but significant HC emissions	This study shows a relatively high temperature gasification with a sustained supply of the producer gas.
[131] **(2011)**	Pelletization and gasification of the biomass materials	Pellets of sugarcane bagasse Pellets of empty fruit bunch Wood	• Biomass consumption rate of 2-3.2 kg/h • Gas flow rate of 4.8-6.8 Nm^3/h was obtained.	• Low density fuels can be easily burnt by making their pellets thus densifying them. • It is good fuel can be burnt even in the absence air.	• Sometimes the cost of pelletization increases the cost of operation of the process, leaving no or very less income.	With the help of pelletization, it is now easy to burn low density fuels, without constructing/designing a separate gasification system

REF. (YEAR)	INVESTIGATION	MATERIAL / FUEL USED	KEY RESULT	ADVANTAGES	DISADVANTAGES	REMARKS
[132] **(2011)**	Improvement of a two stage downdraft biomass gasification system	Carpentry waste	• The two stage gasification system was now operated by supplying air at primary position, whereas pre-mixed air and the producer gas at the secondary position	• High reduction in the tar content of the gas • Increase in the yield and the CV of the gas	• Not observed any.	In order to replace the gas cleaning system, it was a good approach
[133] **(2011)**	Validation of the performance characteristics of a bench scale biomass gasifier	Wood waste and barks Hazelnut shells Olive pulp remains	• The optimal equivalence ratio was 0.35 • Highest CV of the gas was 5.5MJ/Nm^3.	• Due to the introduction of the throat, tar contents were reduced significantly	• In case of low density fuels, there exists a problem of bridging in the raw material hopper, thus chocking the way for the particles to flow	There was no issue in the experimental operation of the modified gasification system.
[134] **(2012)**	Reciprocating engine fired with producer gas	Rice husk	• C.V. of the gas was 6 MJ/Nm^3 • The mean temperature of the Combustion chamber was ~1000^{o}C. • Cold gas efficiency ranged from 50-70%	• Due to the presence of high concentration of nitrogen in the producer gas, knocks were suppressed.	• Decrease in the volumetric efficiency and the power output of the engine	Such system in which nitrogen is present in a sufficiently high amount, can be used where high compression ratios are required.
[135] **(2012)**	Comparative analysis of the gasification characteristics of the pelletized and non pelletized biomass residue.	Rice husk Rice husk pellets	• The engine generated 10kW at 3600RPM • Cold gas efficiency of rice husk and its pellets were 60% and 70% respectively.	• Rice husk pellets require relatively half air as compared to the rice husk and have a relatively higher CV as compared to rice husk.	• Pelletization adds to the cost of power generation.	It is observed that the pellets produce a higher CV gas, which at a large scale operation may compensate the system's operational costs.

REF. (YEAR)	INVESTIGATION	MATERIAL / FUEL USED	KEY RESULT	ADVANTAGES	DISADVANTAGES	REMARKS
[136] **(2012)**	Modelling and experimental analysis of the performance characteristics of a gasifier-engine system	Sugarcane bagasse	• Both the theoretical and the experimental results showed a similar trend. • 16kW at 3600RPM were generated by the engine	• A typical good gas composition was achieved by the gasification system	• No information on emission characteristics	It was a good model as the gasifier was divided in three subparts and each was studied separately.
[137] **(2012)**	Performance evaluation of a diesel engine by using producer gas from some under-utilized biomass on dual-fuel mode of diesel cum producer gas	Wood chips Pigeon pea stalks Corn cobs.	• 60%−64% less specific consumption of diesel in dual fuel mode. • Average diesel substitution of 74% was observed with wood chips followed by corn cobs (78%) and pigeon pea stalks (82%).	• High conventional fuel replacement	• Slightly lower thermal efficiency as compared to the diesel engine.	The study was carried out using optimal parameters such as moisture content, gasification temperature, etc., due to which higher CV of the gas is obtained.
[138] **(2013)**	Performance and Emission Studies of a CI Engine Coupled with Gasifier Running in Dual Fuel Mode	Wood chips Mustard oil cakes	• Reduction in the consumption of Diesel was observed when operated on dual fuel mode • Carbon monoxide and hydrocarbon emission for dual fuel mode was found to be higher than diesel.	• Reduction in the diesel consumption	• Reduction in the brake thermal efficiency • Increase in the HC and CO emissions.	The major pollutants these days are NOx emissions, which in the present study, are suppressed to a great extent.
[139] **(2014)**	Analysis of the trends followed by the performance of a modified SI engine with respect to the ignition timing of the engine	Charcoal	• A gas flow rate of 27Nm3/h was developed • Optimal ignition timing of the modified engine was investigated at low, medium and high speeds	• Very low specific fuel consumption ~0.93kg/kWh at 1700 RPM	• At high speeds, the engine stated decelerating when shifted onto higher load, i.e. >60%	Ignition timing is a very important aspect in order to maximize the power generation and controlling the knocks of the engine.

Chapter 3 Gaps & scope

3.1Gap in Literature:

After the literature review, it is found that a lot of work has been done on production of biodiesel, biogas, landfill gas, etc. and a lot of work is still in progress in these areas. Various factors and methods for production of biodiesel and biogas have been suggested by the researchers. But in the current topic following can be the gap in literature.

- Many biomass materials have been used for the production of producer gas, but sugarcane bagasse is the least tested biomass material.
- Very less literature is available on producer gas-CI Engine system.
- Apart from the performance characteristics of the dual fuel engine, investigation of emission characteristics has not done much.
- The data on the noise characteristics of the dual fuel engine on dual fuel mode operation has not been reported till date.

3.2Scope of future research:

Since there is not much literature available regarding the Biomass-CI engine system, Future scope can be:

- Use of sugarcane bagasse along with woody biomass as a feedstock.
- Use of producer gas in dual fuel CI engine.
- Investigation of the emission characteristics of dual fuel fired CI engine.
- Investigation of noise characteristics of the dual fuel CI engine.

Chapter 4 Methodology & experimental investigation

Introduction:

In the present study, thermal gasification technique of biomass is used for its conversion to a compatible gasesous product that is producer or synthesis gas. This study deals with the investigation of parameters of dual fuel engine fired with blends of diesel and producer gas. Parameters such as performance, emission and noise of a dual fuel engine are studied in the presented work.

4.1 Materials and methods:

The methodology followed for the investigation can be better represented by the following flowchart in Fig 1. These steps are:

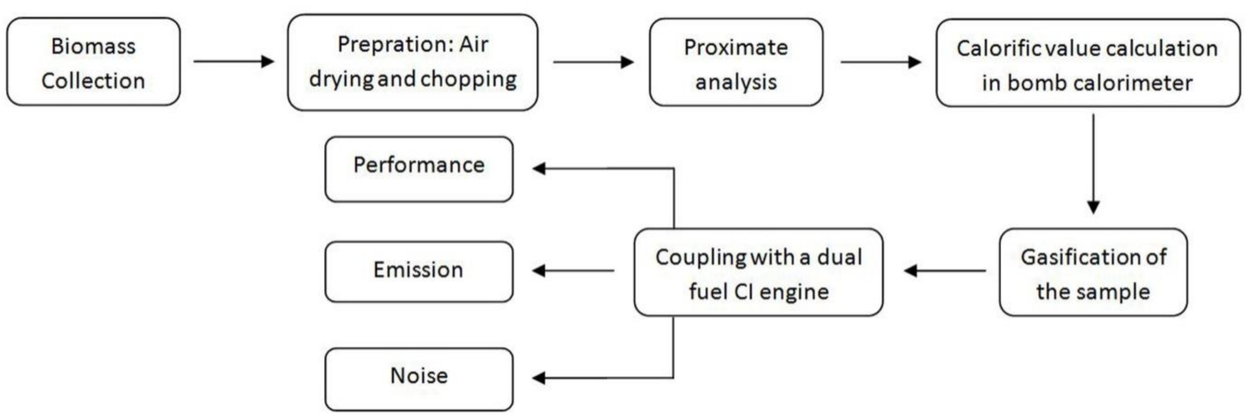

Fig 25 Flow chart of methodology used for the investigation

4.2 Fuel collection:

Fuel used for production of producer gas was sugarcane bagasse. It was collected from a local juice bar owner as it was just a waste for him. At the time of collection, a large amount of moisture was present in it. So, it was sun-dried for one week. After drying it, it was chopped down into small pieces of size ≤ 15mm. The chopped sample was stored in bags for further use. Another biomass fuel selected was wooden chips. It was collected from a carpenter shop. It had a maximum size of 10mm. It was ready to use. Fig 26 shows the images of the fresh, air-dried and chopped sugarcane bagasse (SB) and the carpentry waste (CW).

Fig 26 Processing of raw materials

4.3 Proximate Analysis:

Both the biomass samples were to be tested in the lab for their proximate analysis. Small crucibles were used for the analysis. 2 gm sample of each biomass material was taken in two different crucibles. The samples were placed in an electric oven for removal of moisture from them. After heating the samples for half an hour (30 minutes) they were taken out and stirred with the help of a stirrer so as expose the lower biomass to the hot air for efficient evaporation. After stirring they were kept in the oven for half an hour (30 minutes) again.

Table 6 Size and moisture specifications of raw materials

Raw material	**Size**		**Moisture**	
	Before processing	**After processing**	**Before processing**	**After processing**
Sugarcane bagasse	Fibers of 2m length (maximum)	0.1mm to 0.99mm (~10%) 1mm to 25mm (~90%)	>50%	<9%
Carpentry waste	5mm to 20mm		<10%	

After removing the samples from the oven, they were placed in a desiccator. The samples were weighted again and the reduction in mass indicated the moisture content in each sample. To analyze the VM (Volatile Matter), the samples were heated at 240^{o}C in a muffle furnace for half an hour. After cooling the samples in a desiccator, they were weighted. This loss in mass indicated the VM in each sample. Further the samples were heated in the furnace at 600^{o}C and burnt to ashes. Finally the samples were weighted again and this loss in mass indicated the ash content in the sample. These samples were tested for proximate analysis according to ASTM D7582 – 15 standard and the result of proximate analysis is shown in table 7.

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

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

4.4 Calorific value:

The calorific values (CV) of both the fuels were calculated using a bomb calorimeter. The rise in temperature of water was noted for the calculation of CV. Following relation is used to calculate the CV:

$$CV = {}^{2382.32 \times \Delta T}/_{x} - (E1 + E2)$$

ΔT = Rise in temperature of 2000g of water

x = Mass of fuel used

$E1 + E2$ = weight of nichrome wire and cotton thread

The calculated values of CVs for SB and CW are shown in table 7.

Table 7 Proximate analysis and calorific value of SB and CW

Component	**Sugarcane bagasse**	**Carpentry waste**
Volatile matter (%)	76.58	72.05
Moisture (%)	8.48	9.2
Fixed carbon (%)	12.02	17.71
Ash (%)	2.92	1.04
Calorific value (kJ/kg)	18342.65	18773.60

4.5 The gasifier system:

For the experimental purposes a downdraft gasifier with a throat was used. The specifications of the gasifier are provided in table 8 and are in accordance to the catalogue provided by the manufacturer.

Table 8 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

Permissible moisture content	<20%
Gas flow rate	25 Nm^3/hr (Maximum)
Thermal output	30.21 kW
Typical gas composition	CO = 19±2%, CH_4 ≤ 4%, H_2 = 18±2%, CO_2 = 10±4%, N_2 = 51%
C.V. of the producer gas produced	4393.2 kJ/Nm^3 to 5439.2 kJ/Nm^3
Fuel Consumption	8-10 kg/hr

4.6 Firing of the gasifier:

In order to start the gasification process, both the raw materials in 50:50 ratio are mixed thoroughly and introduced manually into the hopper from the top.

4.7.1 Issues in the feeding system:

Since sugarcane bagasse is a low density material, so due to light weight, problems were faced in the feeding system. It was earlier known that the throat of the downdraft gasifier has a cross-sectional diameter of ~50mm so the sugarcane bagasse was initially chopped into pieces of < 20mm size. Still due to the light weight of the particles, they were unable to flow in the downward direction, even when the hopper vibrator was turned on. Also, due to the presence of the throat, the phenomenon of bridging among the particle occurs, in which the lower particles support the weight of the upper particles ad stop their downward flow.

4.7.2 Remedies:

Following are the suggested remedies:

- Using a fuel densification technique, i.e. instead of loose feeding of the fuel, use of pellets or briquettes of the same fuel.
- Usage of a fluidized bed or entrained flow gasifier instead of a fixed bed gasifier.
- Replacement of the throat gasifier with a throatless gasifier.

After feeding the raw material, hopper top is sealed firmly by a fastener so that no air enters from the top. Air flow is induced inside the gasifier due to the draft created by the scrubber. Gasifier is fired from the air inlets using a diesel torch. After 15-20 minutes of operation, the gas starts forming and it can be seen burning at the flare burner. The the gas leaves the gasifier at a temperature of ~450^{o}C.

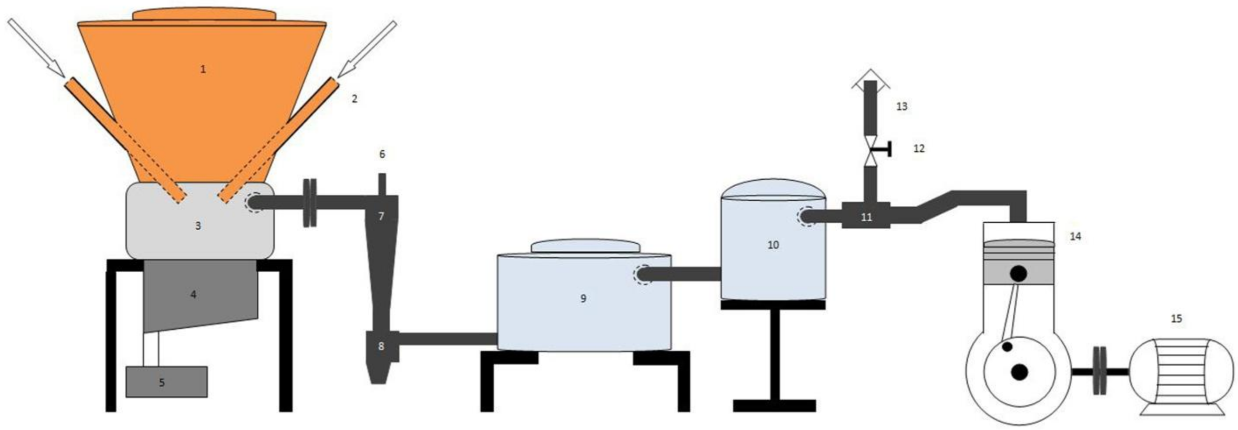

Fig 27 Schematic diagram of the experimental setup. 1: Hopper and Zone 1 – Drying & pyrolysis, 2: Air inlet, 3: Zone 2 – Combustion, 4: Zone 3 – Reduction, 5: Drain tub for ash removal, 6: Water inlet for the scrubber, 7: Scrubber for cooling and cleaning of gas, 8: Drain box, 9: Secondary filter for tar, particulate and moisture removal, 10: Safety filter for ultra cleaning of gas, 11: Bypass valve, 12: Flare control valve, 13: Flare burner for testing gas quality, 14: DFCI engine test setup, 15: Eddy current dynamometer.

4.7 Gas cleaning:

Since the gas produced had a high temperature (~450^{o}C), was very dirty in nature and contained some amount of tars, so it needed cleaning and cooling before its use in the dual fuel CI engine (DFCI). For this purpose a cleaning and cooling unit was used just at the exit of the gas from the gasifier. The gas was first passed through a water spray, which cooled the gas and removed the excessive soot particles and tars by condensing them. This gas was further passed through a secondary filter, which contains sawdust and wood chips. This filter absorbs moisture and traps the soot particles if any. To ensure complete cleaning of the gas, the gas was passed. through a safety filter which provides a clean and less odory gas. This gas was ~99% pure and had a temperature of 30^{o}C-45^{o}C so, it was now clean enough to be used in the DFCI engine

Fig 28 Down draft gasifier setup

Fig 29 Charcoal Filter And Safety Filter

Fig 30 Small/Narrow intake port for air/oxygen intake

4.8 Dual fuel CI engine setup:

The ultra clean gas obtained after the cleaning process was introduced into the DFCI engine by mixing it with intake air in a carburetor. An orifice type flow meter was used to measure flow rate of the producer gas, which 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.

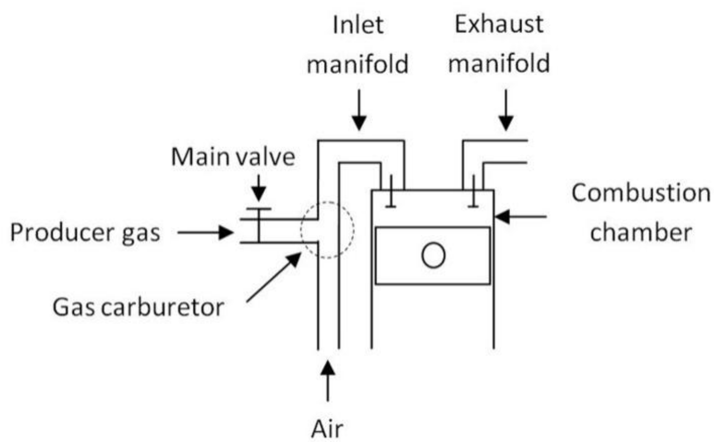

Fig 31 Schematic diagram showing introduction of producer gas into the DFCI engine.

Fig 32 Variable CR dual fuel CI engine setup

Fig 33 Flowmeter for measuring the volume flow rate of producer gas

The DFCI engine was a four stroke compression ignition water cooled engine. This engine was a constant speed engine and the speed fluctuations were controlled by a governor. Table 6 shows the details about the DFCI engine setup specifications:

Table 9 Specifications of the DFCI engine setup

Parameter	Specification
Engine make	Kirloskar
Engine model	AV-1
Engine type	VCRE (Variable Compression Ratio (CI) 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

The various emission and noise parameters of the DFCI engine were studied by keeping the compression ratio of the engine fixed at 18. The gas flow rate was controlled by adjusting the flow control valve and a fixed the flow rate of 5.07Nm^3/hr of gas was used. The subsequent increase in the flow of the gas resulted in a decrease in the flow rate of the gas, which keeps the volumetric efficiency of the engine constant. 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. The engine was tested on the following two modes:

- On single fuel mode using diesel oil.
- On dual fuel mode using diesel oil as the primary fuel and producer gas as secondary fuel.

Before starting the engine-setup, water valve was opened to supply cooling water to the water jacket and the calorimeter. The water supply as 250 LPH and 75 LPH were supplied to the engine as well as the calorimeter. The engine was tested for six load variations from 2kg to 12kg. Air flow and gas flow were recorded using two separate orifices of 20mm and 15.31mm diameters respectively. The values corresponding to each load were averaged to single value to get a better graphical representation. All the graphs are represented using these averaged values of the corresponding parameter for both the modes.

4.9Reflections:

Error is a recognizable deficiency in a part/section of the working process, which is not caused due to lack of knowledge. The sources of error in any process are dependent on the type of process and the accuracy of the equipments. In the present reported work, there are some sources and equipments, where there may be or is a chance of error. These sources/ equipments with their error analysis are given below:

Table 10 Reflections

Source/equipment	Error analysis	Improvement/modification
1. Flowmeter	▪ Error in reading the differential scale ▪ Leakage in the any part of the flowmeter such as the coupling joint, the pressure tubes etc.	▪ Proper attention should be paid while reading the differential value of the scale ▪ It should be made sure that the coupling has a proper gasket and the joints of the pressure tube must be sealed with a sealing tape.
2. Exhaust gas analyser	▪ Error due to improper insertion of the probe ▪ Low accuracy of the equipment as it gives different results on different time at same working conditions.	▪ The probe should be such inserted that only some amount of the exhaust gas passes into the analyser and the rest should bypass it. ▪ There should be some calibration unit also with the equipment in order to get a better accuracy in the results.

Source/equipment	Error analysis	Improvement/modification
3. Sound level meter	▪ Operation of the device without the windscreen ▪ Inappropriate distance from the noise source.	▪ The device should be operated using a wind screen on the microphone as without it the noise of air will also be included in the results. ▪ The sound level should be measured from a distance of approximately 1 meters from the noise source.

Chapter 5 Results

5.1Combustion characteristics of the DFCI engine:

In order to investigate the combustion characteristics of the DFCI engine, various pressure transducers were used in the combustion chamber and thermocouples gave the values of temperature at various points. The information provided by the pressure transducers and the thermocouples was sent to the ICE test rig, which amplified the signals and sent to the computer. In computer, "ICenginesoft 9.0" software provided by Apex Innovations Pvt. Ltd. was used to interpret the amplified results. The combustion characteristics provided by the software are as follows:

5.1.1 Cylinder pressure:

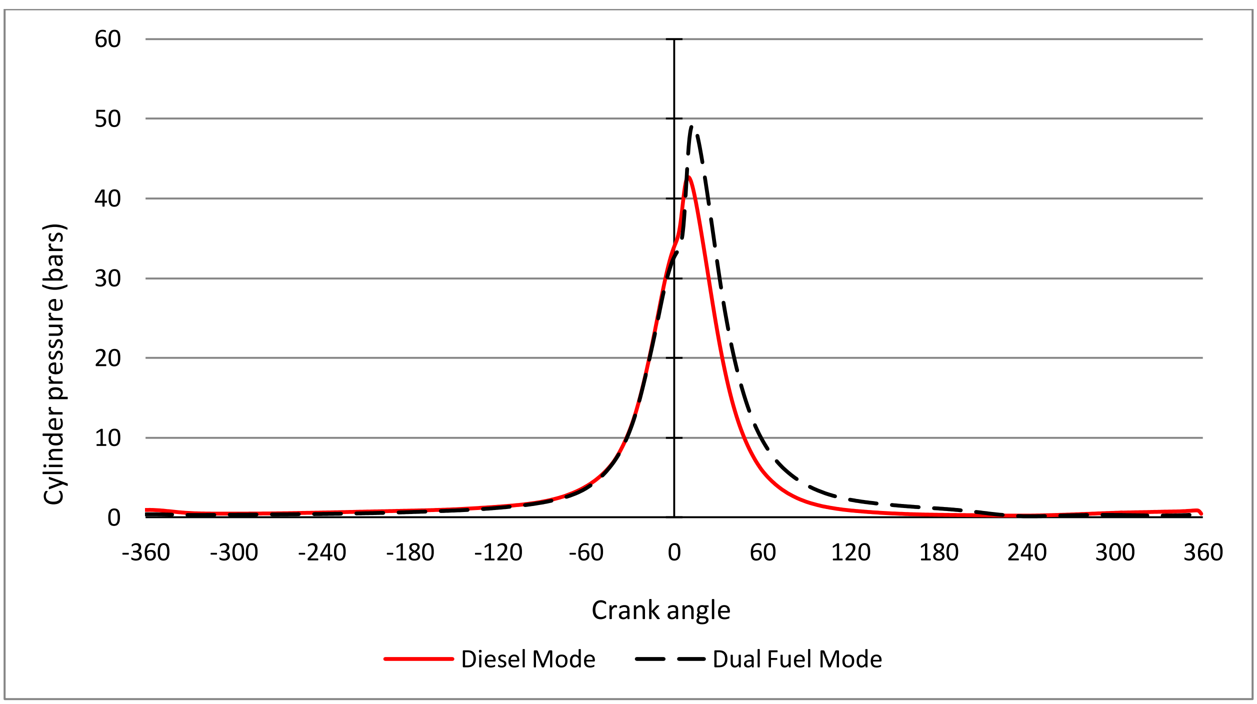

Fig 34 Variations of cylinder pressure with crank angle

In Fig 34 the variation of cylinder pressure is plotted with respect to the crank angle. The maximum pressure reached in case of the pilot fuel mode was less as compared to the dual fuel mode. The maximum pressure in case of diesel mode was 42.63 bar and it was seen at 10^{o}

after TDC (Top Dead Center) whereas the peak pressure of 49.3 bar was recorded in case of dual fuel mode at an angle of 13^o after TDC.

5.1.2 Mean gas temperature:

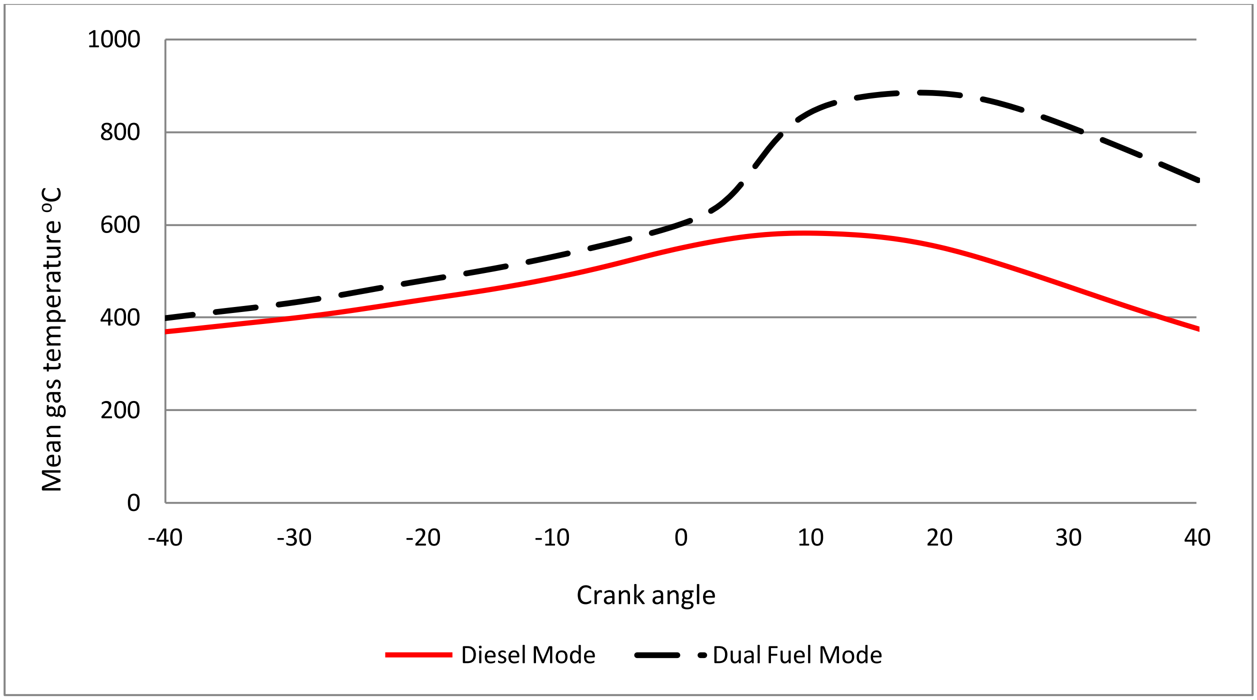

Fig 35 Plot for mean temperature of the gas with crank movement.

In this case the mean temperature of the gas was investigated by taking the readings for 10 cycles. All the values of the 10 cycles for each degree (^{o}) of crank were averaged to a single value and plotted on the graph. It is observed that the diesel mode shows a regular trend and a slight increase in the mean gas temperature after and near the TDC followed by a decrease in the same fashion. Whereas in dual fuel mode, it is observed that mean gas temperature is slightly higher than the dual fuel mode upto TDC. As soon as the diesel injection starts after TDC, there is a sharp rise in the mean temperature of the gas. It is observed that the maximum values of the mean temperature are 582.56^{o}C (at 10^o) and 885.59^{o}C (at 18^o) in diesel and dual fuel modes respectively.

5.1.3 Net heat release:

In this investigation, the trend for the net heat release was obtained for the various angles of the crank. In both the cases, it is found that the maximum heat is released near the TDC

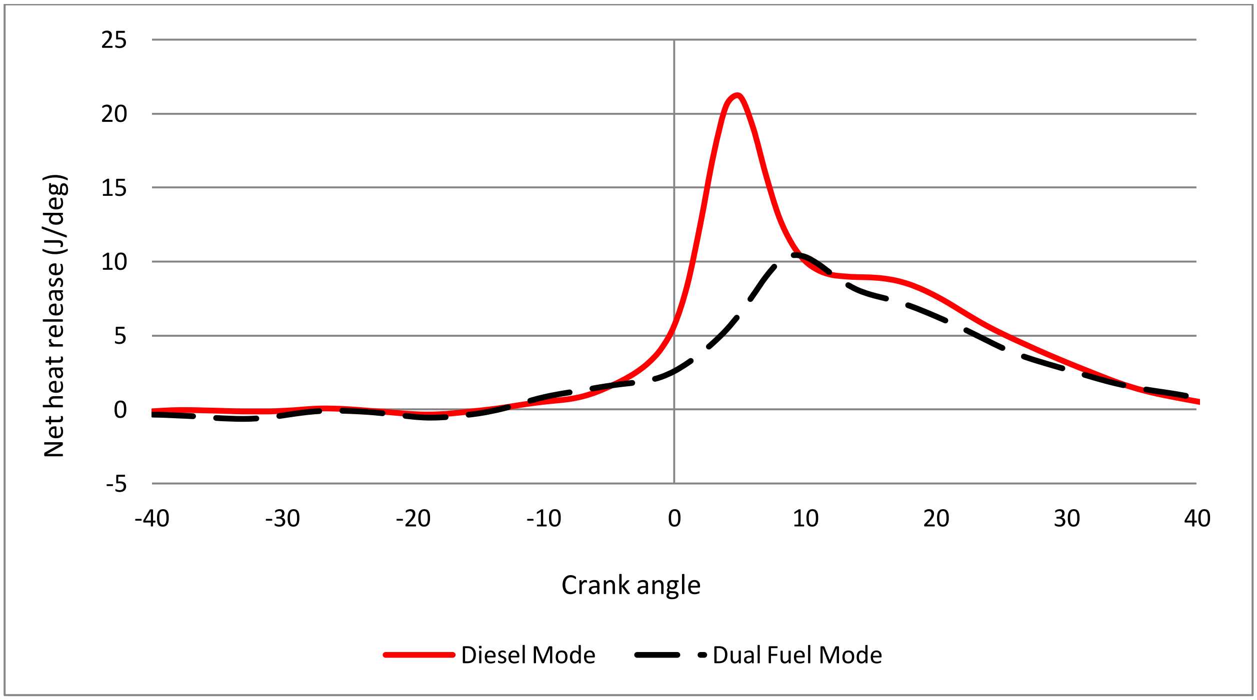

Fig 36 Net heat release with respect to crank angle

At an angle of 5^o before TDC, an increase in the net heat release is noted in both cases but more in case of diesel mode. At TDC there is a sharp rise in the net heat release and a peak value of 21.2 J/deg was observed at 5^o after TDC in diesel mode. Whereas in case of dual fuel mode, an increase is noticed, but not as sharp as in the case of diesel mode. The peak value of 10.43 J/deg was observed in the case of dual fuel mode.

5.2Emission characteristics of the DFCI engine:

In order to investigate the emission characteristics of the DFCI engine, "Maxicem Portable Gas Analyser" model ACE-8000 was used. The records reported by this device are represented below:

5.2.1 Hydrocarbon emissions (HC):

As indicated by fig 12, there is a significant increase in the HC emissions of DFCI when operated on dual fuel mode. This increase can be explained by the following two reasons: the reason one is that when engine is operated at dual fuel mode, keeping the volumetric efficiency of the engine as constant, the volume of air inside the combustion chamber is reduced due to its replacement with producer gas, due to which there prevails a condition of insufficient oxygen so, some part of the fuel comes out uncombusted. The other reason is the improper mixing of the fuel, which results into the poor combustion and hence more concentration of HCs is recorded.

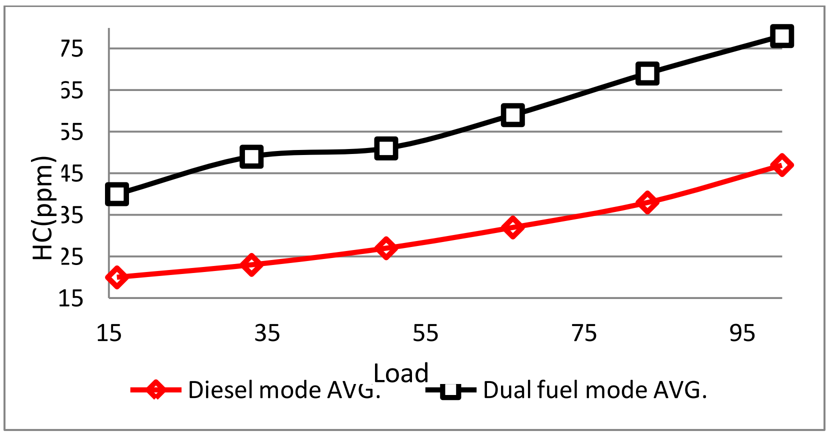

Fig 37 HC emissions with load variation.

5.2.2 Carbon monoxide emissions (CO):

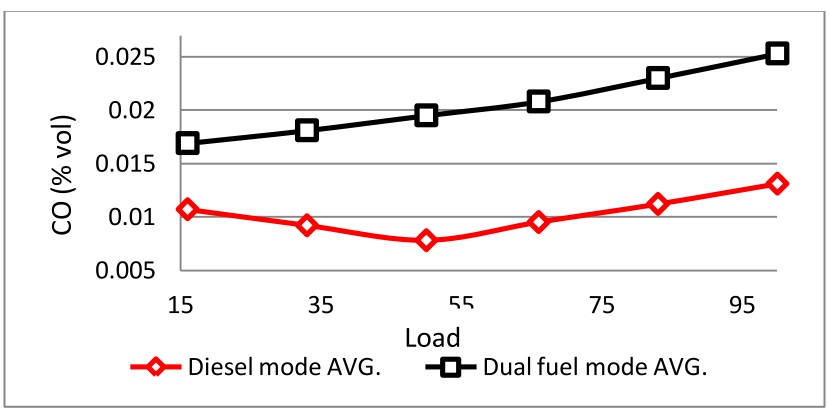

Fig 38 CO emissions with load variation.

The emissions of CO at the dual fuel mode of the DFCI engine shows greater concentrations as compared to the diesel mode as indicated in fig 13. In this case also the reason behind the increase in the CO concentration in the exhaust gas is the incomplete combustion, which occurs due to insufficient oxygen and poor fuel mixing. On dual fuel mode, a maximum of 0.0253 volume percentage of CO was emitted at 100% load.

5.2.3 Nitrogen oxide emissions (NOx):

It is clearly depicted in fig 14 that with the increase in the load, the engine shows an increasing trend of NOx concentration. The reason for this trend is that at higher loads, more fuel is injected into the combustion chamber, on burning, it increases the temperature of the combustion chamber and at high temperature, the nitrogen (N_2) reacts with the oxygen and forms various types of oxides. But in the case of the dual fuel mode, a significant reduction in the NOx is noted. This is due to decrease in the temperature of the combustion because of incomplete combustion of the fuel. Maximum concentration of the NOx in the exhaust gas is 42 ppm.

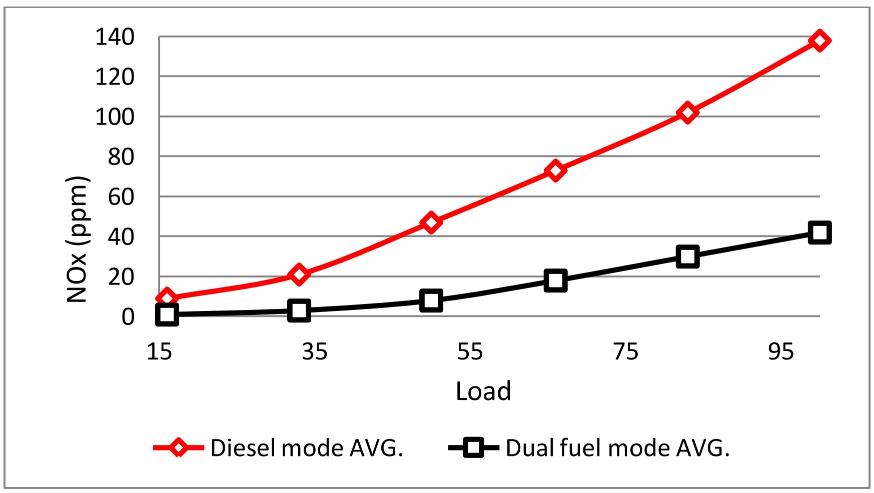

Fig 39 NOx emissions with load variation.

5.2.4 Exhaust gas temperature:

As indicated by fig 15, in both the cases the temperature of the exhaust gas shows an increase on increasing the load values. This is due to the fact that at higher loads more fuel is injected and it produces more heat and hence higher temperatures

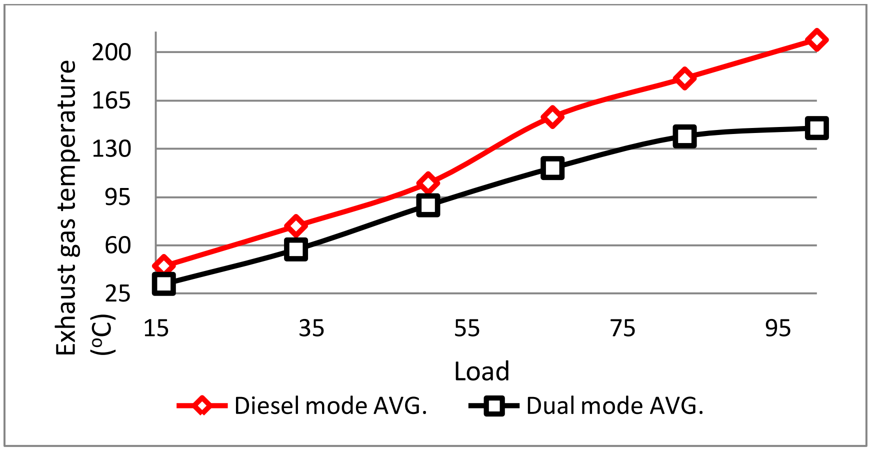

Fig 40 Exhaust gas temperature with load variation.

But in case of the dual fuel mode, the maximum temperature of the exhaust gas is 145°C whereas it is 209°C in case of diesel mode. The reason for this is the incomplete combustion and low C.V. of the gas.

5.3Noise characteristics:

For this investigation, "CESVA Sound Level Meter and Spectral Analyser" model SC310 was used. The sound level observed using this device are shown below:

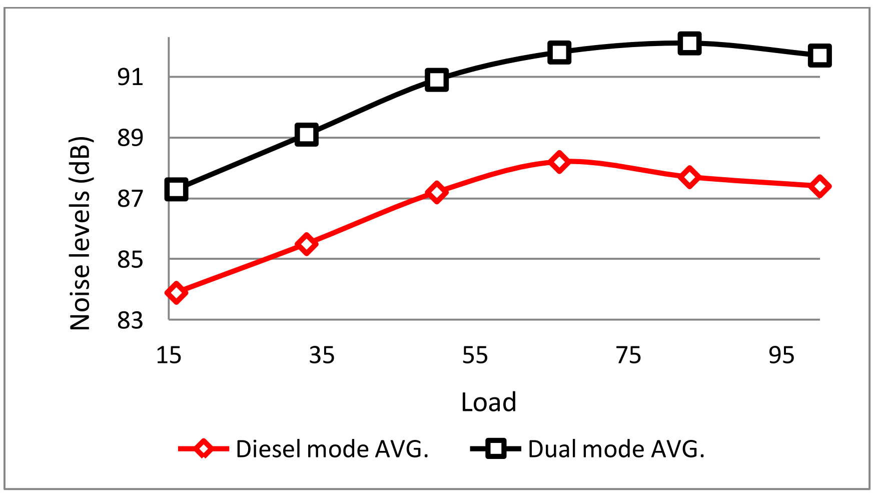

Fig 41 Variation of noise levels with variation in load.

As shown in fig 16, 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 Validation of the results

For the success and authenticity of any research, it is necessary that the key results of that research are validated with the present expert literature. In this section, a similar attempt has been made to validate the results of the reported work with the previously published expert literature in this field. It is observed that due to the use of averaged values of the three trails, the result could be validated to a great extent.

6.1 HC Emissions:

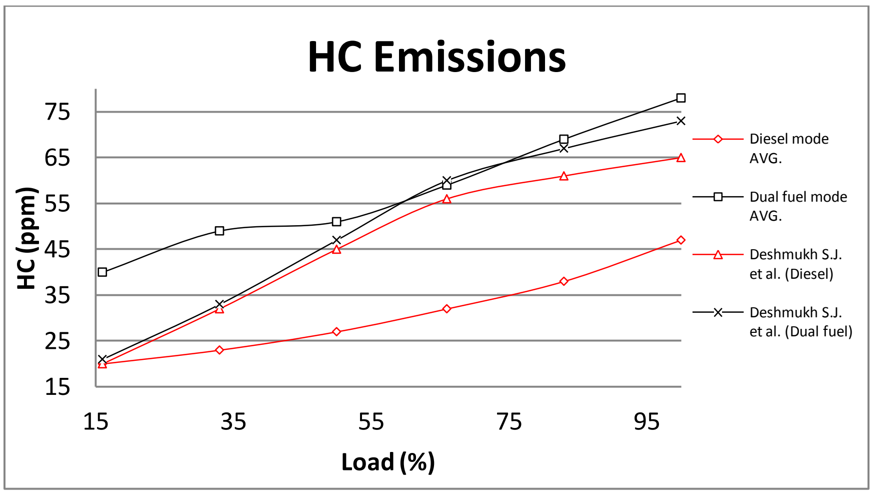

Fig 42 Comparison of HC emissions with the previous literature

The fig shows a comparison of the experimental results of HC emissions in the present work and those reported by Deshmukh S.J. et al (2008) [140]. It is observed that at lower loads, the HC emission characteristics are almost same for diesel mode in both the cases. In case of dual fuel mode, the present work reports a greater concentration of HCs at lower loads (<35%), whereas a similar trend is seen at higher load and the values are quite close to each other, which gives an indication that the results could be validated and correct to a great extent. Maximum concentrations of HC were 78 ppm and 73 ppm in the case of dual fuel mode in the present work and the previous literature respectively, which are quite close to each other.

6.2 CO emissions:

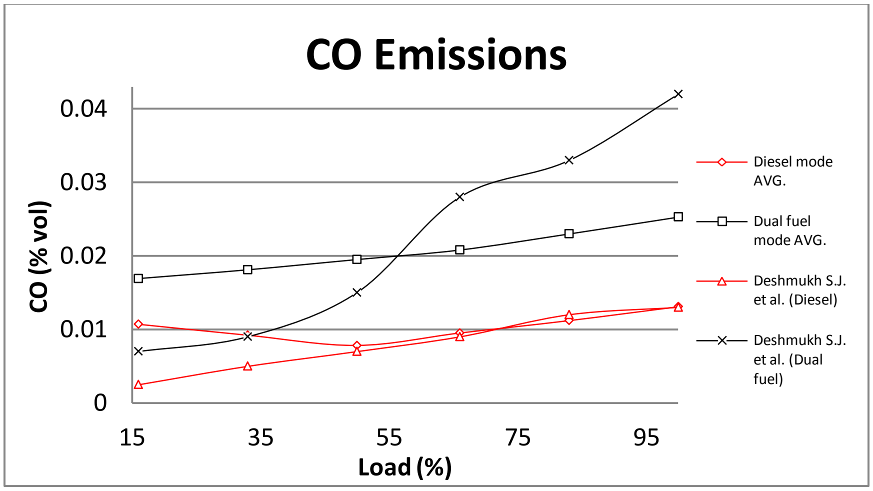

Fig 43 Comparison of CO emissions with the previous literature

The trend for CO emissions in the present work are compared with the results reported by Deshmukh S.J. et al 2008 [140]. In this comparision it is found that at lower loads, the present work shows a greater concentration of CO as compared to the previous literature on diesel mode, whereas at higher loads, the loads are almost same and superimposing at some places. In case of dual fuel mode, at lower loads, the previous literature shows a lower concentration of CO whereas take a sharp increase at the higher loads (>50%). The values of CO emissions at higher loads are quite high in the case of previous literature as compared to the present literature, whereas at lower load the results are quite comparable with each other. In this case the maximum part of the investigation shows a similar trend except the one showed by the previous literature on dual fuel mode at higher loads.

6.3 NOx emissions:

These results were compared with the result reported by Shrivastava V. et al 2012 [141]. From the comparison, it is concluded that the previous literature reports greater concentrations of NOx as compared to the present literature. The reason for this trend is that a bigger engine (in terms of power) of rated power 4.4kW, was used for the analysis, so it emitted greater amounts NOx. As it is clear from the comparison that a similar trend is reported by the present work as reported by the previous work. Taking into account the scale factor, it would be justifiable to validate the results.

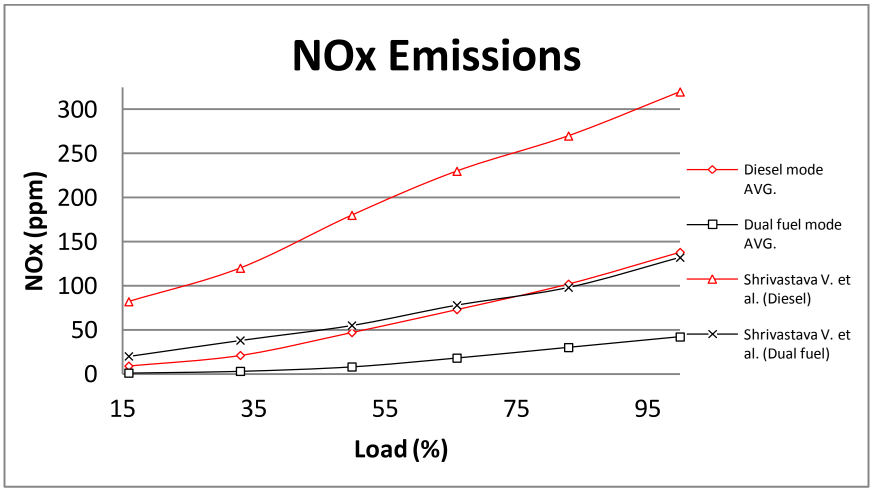

Fig 44 Comparison of NOx emissions with the previous literature

6.4 Exhaust gas temperature:

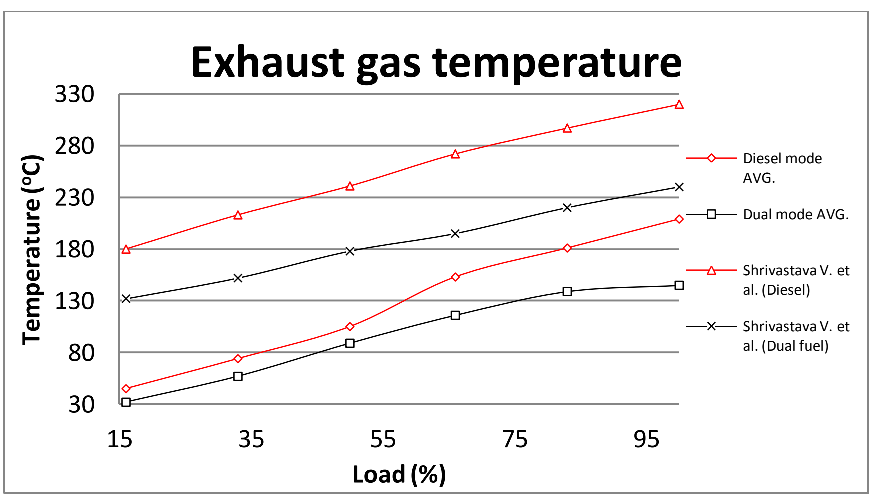

Fig 45 Comparison of Exhaust Gas Temperature with the previous literature

These results are also compared to those reported by Shrivastava V. et al (2012) [141]. The exhaust gas temperature shows a similar trend in the present literature as reported by the previous literature but, with a scaled up set of values. Again, due to the larger size of the engine, more fuel burns, which produces more heat and hence hotter exhaust gas. Although the values of exhaust gas temperature are quite different from each other, yet the trend lines in all the four cases are identical to a great extent, which validates the reported results.

6.5 Noise Characteristics:

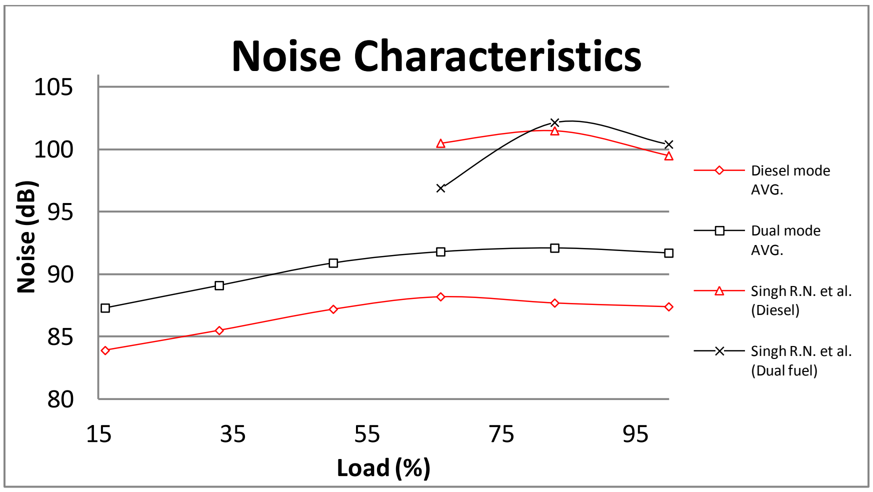

Fig 46 Comparison of Noise Characteristics with the previous literature

As discussed in the beginning, there is not much literature, reporting working on noise characteristics, so it was quite difficult to find a literature to validate the present work. The noise characteristics of the engine were compared with the work reported by Singh R.N. et al (2007) [123]. Due to lack of reported work, significant comparison could not be made but the analysis of the results showed that the result are correct to some extent. In the previous literature, it is reported that on dual fuel mode, there is an increase in the noise characteristics of the engine. It shows an increase of ~ 1 dB of noise when the engine is operated on the dual fuel mode. In the present literature also it is reported that on the dual fuel mode, there is an average increase of ~3 dB of noise. So, this validates the results.

Chapter 7 Discussion

7.1 Combustion characteristics of the DFCI engine:

This work is not reported in most of the literature and the combustion characteristics of a single fuel engine are reported in most of the research articles. It takes a lot of time to analyze such a big set of readings (720 readings/plot) so the researchers try to skip this part. But in the present work, combustion analysis as far as possible is reported. Following is the detailed analysis of the combustion results:

7.1.1 Cylinder pressure:

It is observed that the peak pressure is higher in the case of dual fuel mode as compared to the diesel mode. This can be explained as: In the case of dual fuel mode, air and the gaseous fuel are compressed and when the compressed charge approaches the TDC, it is on the verge of burning and the temperature of the air-gas mixture is slightly lower than its self ignition temperature. When this hot air-gas mixture gets an injection of diesel at a high pressure, there is a sudden combustion in the whole region. No flame front is formed, the whole charge burns collectively. Due to this, there is a sharp rise in the pressure in the case of dual fuel mode.

7.1.2 Mean temperature of gas:

In this investigation, again a sharp increase in the mean gas temperature is noted in the case of dual fuel mode. As explained earlier, due to the sudden burning of the charge, there is a sharp increase in the average/mean temperature of the gas. Also, due to the governor system, more fuel is injected than the required amount on the dual fuel mode, which causes more fuel to burn and increases the mean temperature of the gas.

7.1.3 Net heat release:

In this investigation, it is observed that the dual fuel mode radiates/releases heat at a lower pace whereas the diesel mode releases heat quite faster. The reason for this trend is the incomplete combustion in the case of dual fuel mode. Due to air deficiency, the charge is not able to burn completely so the heat release rate decreases in the dual fuel mode.

7.2 Emission characteristics of the DFCI engine:

The reported work focused on the effect of dual fuelling on the emission characteristics of the DFCI. Since earlier work was only limited to the performance characteristics of the DFCI engine and also specifically sugarcane bagasse was not used for the production of producer gas, so this provided a motivation to work on this specific area. It was observed that engine showed a smooth running characteristics with a significant reduction as well as an increase in the emission characteristics. The detailed analysis is given below:

7.2.1 Hydrocarbon (HC) emissions:

On pilot fuel mode, the engine shows relatively lower HC emissions as compared to the dual fuel mode. The hydrocarbon emissions follow an increasing trend in both the modes and almost same slope is observed in both the cases. The engine used for the experimental analysis has a constant volumetric efficiency, i.e. it can inhale a specific quantity of gaseous fluid at all the times. The gaseous fluid can be only air (pilot fuel mode) or mixture of air and producer gas (dual fuel mode). On dual fuel mode, some amount of air, which was initially (on pilot fuel mode) going into the combustion chamber is now replaced by the producer gas. Due to this an air deficient atmosphere is created in the combustion chamber or it can be said that the engine is now supplied with rich fuel mixture. This causes an incomplete combustion of the fuel due lack of air/oxygen in the combustion chamber. So, some part of the fuel comes out uncombusted or partially combusted. This is the reason for the trend followed by the HC emissions.

7.2.2 Carbon monoxide emissions (CO):

The CO emissions show an almost linearly increasing trend with load variations on dual fuel mode. The CO emissions are more in case of dual fuel mode. As discussed in the previous section, due to an air deficient atmosphere, it is observed that some part of the fuel does not take part in the combustion process. So, a significantly higher concentration of the CO is found in the exhaust gas.

7.2.3 Exhaust gas temperature:

The exhaust gas temperature shows an increasing trend in both the cases. This due to the reason that at higher loads, more fuel is injected into the cylinder, which produces a more amount of heat and hence the exhaust gas becomes hotter with an increase in the load on the engine. On dual fuel mode, relatively lower exhaust gas temperature is observed at all load values in comparison to the pilot fuel mode. Two reasons support this trend. The first one is that due to the air deficient atmosphere, lesser amount of fuel gets actually burnt, due to this lesser heat is generated, so the exhaust gas is less hotter in comparison to the exhaust gas in the pilot fuel mode. The second reason is that the producer gas is a low C.V. gas, due to which relatively low heat is generated, which cause the exhaust gas to get less hotter.

7.2.4 Nitrogen oxide emissions:

The NOx emissions show a linear trend and the NOx concentration in exhaust increases in both the cases but with different slopes. In case of pilot fuel mode, it is observed that the engine emits a greater amount of NOx as compared to the dual fuel mode. The above stated reasons are responsible for this trend also. The concentration of NOx emissions depends on the temperature of the combustion chamber. As discussed earlier, lesser amount of heat is generated in the combustion chamber, so lesser concentrations of NOx are found in the exhaust gas. The present work reports, a maximum reduction of 69.5% in the NOx emission.

7.2.5 Improvement/modification in the existing setup:

It is observed that due to air deficiency in the combustion chamber, the CO and the HC emissions are significantly increased. One of the possible improvement or modification can be sending a more amount of air using a supercharger or a turbocharger. This will help in sending more mass of air in the combustion chamber in spite of the constant volumetric efficiency. Due to this a greater amount fuel can be burnt, hence reducing the overall concentration of HC and CO in the exhaust gas. Another modification can be the replacement of the governor with a manual injection system. This is because even on the dual fuel mode, i.e. on injection of a gaseous fuel, the governor keeps on injecting a higher volume of fuel than the required amount. By this modification, the volume of fuel to be injected could be controlled by manually fixing the position of the accelerator. Now corresponding to the quantity of the air, a lesser volume of fuel is injected, which will be better combusted and hence will result in a reduction in the CO and HC emissions.

7.3Noise characteristics of the DFCI engine:

The combustion noise in an engine is dependent on various chemical and the physical properties of the fuel. The physical properties include density, viscosity, bulk modulus, etc. In the previous research, it has been reported that with an increase in density and viscosity of the fuel, there is a significant reduction in the noise of the engine. Where as if the density and the viscosity of the fuel is decreased, it results in an increase in the noise of the engine. In the present work on dual fuelling, the density as well as the viscosity of the air, gas and diesel mixture gets decreased, which results in an increase in combustion noise and hence the exhaust noise also.

Chapter 8 Conclusion

From the physical observations, it is concluded that the engine shows a smooth and sustained working with a slight increase in the noise. From the analysed results, the following are concluded:

- Dual fuelling with the gasification derived producer gas is a good concept of generating valuable energy from a waste.
- Valuable conventional fuel can be significantly replaced using gasifier-dual fuel engine system.
- At present the engine showed an increased concentration of HC and CO but, a slight modification as stated earlier can make the system better in terms of emission characteristics
- Dual fuel operation results in a decrease in the NO_x emissions as well as the exhaust gas temperature, with a slight increase of ~ 3.4 dB in the noise emissions.
- The gasifier-dual fuel engine system will be a popular energy generation system in the coming years.

Chapter 9 Future scope

As it is known that India is an agriculture based country so there is a large resource of never ending “bio-energy”. Also the whole world and specifically India is facing the shortage of Conventional fuels, on which the whole economy of the country is dependent, so biomass appears to be promising resource in the coming days. Out of various biomass to energy conversion processes, biomass gasification is an emerging technique. Due to the high carbon conversion efficiency and the pollution free nature, of this process, it is gaining popularity these days. The setup used in the present investigation worked well in almost all the aspects. Still, in order to further improve the output of the present system, the following can be expected in future:

- Modification of the gasifier feeding system or designing and fabrication of a downdraft gasifier, so that it becomes easy to gasify low density, biomass materials such as sugarcane bagasse, cotton stalk, mustard sticks etc.
- Practical investigation of the effect of equivalence ratio on the quality and composition of the producer gas.
- Use the biomass gasifier system with a charged engine, i.e. supercharged or turbocharged engine.
- Experimental investigation of the effect of the injection timing on the combustion, performance, emission and noise characteristics of the DFCI engine.
- Investigation of noise characteristics of the DFCI engine.

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Appendices

Appendix A

The following tables represent the compete supplementary data related to the emission and noise characteristics in the present study.

Table 11 HC emissions with respect to load variations on diesel and dual fuel modes

Load (%)	Diesel mode AVG. (ppm)	Dual fuel mode AVG.(ppm)
16	20	40
33	23	49
50	27	51
66	32	59
83	38	69
100	47	78

Table 12 CO emissions with respect to load variations on diesel and dual fuel modes

Load (%)	Diesel mode AVG. (%vol)	Dual fuel mode AVG. (%vol)
16	0.0107	0.0169
33	0.0092	0.0181
50	0.0078	0.0195
66	0.0095	0.0208
83	0.0112	0.023
100	0.0131	0.0253

Table 13 NOx emissions with respect to load variations on diesel and dual fuel modes

Load (%)	Diesel mode AVG. (ppm)	Dual fuel mode AVG. (ppm)
16	9	1
33	21	3
50	47	8
66	73	18
83	102	30
100	138	42

Table 14 Exhaust gas temperature with respect to load variations on diesel and dual fuel modes

Load	Diesel mode AVG.	Dual mode AVG.
16	45	32
33	74	57
50	105	89
66	153	116
83	181	139
100	209	145

Table 15 Noise characteristics with respect to load variations on diesel and dual fuel modes

Load	Diesel mode AVG.	Dual mode AVG.
16	83.9	87.3
33	85.5	89.1
50	87.2	90.9
66	88.2	91.8
83	87.7	92.1
100	87.4	91.7

Appendix B

The following tables represent the data from some other literatures, with which the present work is validated

Table 16 Validation of HC emissions with the previous reported work

Load	Diesel mode AVG.	Dual fuel mode AVG.	Deshmukh S.J.et al. (Diesel)	Deshmukh S.J. et al. (Dual fuel)
16	20	40	20	21
33	23	49	32	33
50	27	51	45	47
66	32	59	56	60
83	38	69	61	67
100	47	78	65	73

Table 17 Validation of CO emissions with the previous reported work

Load	Diesel mode AVG.	Dual fuel mode AVG.	Deshmukh S.J. et al. (Diesel)	Deshmukh S.J. et al. (Dual fuel)
16	0.0107	0.0169	0.0025	0.007
33	0.0092	0.0181	0.005	0.009
50	0.0078	0.0195	0.007	0.015
66	0.0095	0.0208	0.009	0.028

83	0.0112	0.023	0.012	0.033
100	0.0131	0.0253	0.013	0.042

Table 18 Validation of NOx emissions with the previous reported work

Load	Diesel mode AVG.	Dual fuel mode AVG.	Shrivastava V. et al. (Diesel)	Shrivastava V. et al. (Dual fuel)
16	9	1	82	20
33	21	3	120	38
50	47	8	180	55
66	73	18	230	78
83	102	30	270	98
100	138	42	320	132

Table 19 Validation of exhaust gas temperatures with the previous reported work

Load	Diesel mode AVG.	Dual mode AVG.	Shrivastava V. et al. (Diesel)	Shrivastava V. et al. (Dual fuel)
16	45	32	180	132
33	74	57	213	152
50	105	89	241	178
66	153	116	272	195
83	181	139	297	220

100	209	145	320	240

Table 20 Validation of Noise characteristics with the previous reported work

Load	Diesel mode AVG.	Dual mode AVG.	Singh R.N. et al. (Diesel)	Singh R.N. et al. (Dual fuel)
16	83.9	87.3	-	-
33	85.5	89.1	-	-
50	87.2	90.9	-	-
66	88.2	91.8	100.5	96.9
83	87.7	92.1	101.5	102.15
100	87.4	91.7	99.5	100.4

Appendix C

The following tables represent the variations of various combustion parameters such as cylinder pressure, net heat release, mean gas temperature with respect to the crank angle.

Table 21 Cylinder pressure change with respect to crank angle in diesel and dual fuel mode

Crank Angle	Diesel mode	Dual Fuel mode
-360	0.91	0.39
-359	0.91	0.4
-358	0.91	0.4
-357	0.92	0.4
-356	0.91	0.4
-355	0.91	0.4
-354	0.9	0.4
-353	0.89	0.4
-352	0.88	0.4
-351	0.87	0.39
-350	0.86	0.39
-349	0.84	0.39
-348	0.83	0.38
-347	0.81	0.38
-346	0.79	0.37
-345	0.77	0.37
-344	0.76	0.36
-343	0.74	0.36
-342	0.72	0.35
-341	0.7	0.35
-340	0.68	0.34
-339	0.66	0.34
-338	0.64	0.34
-337	0.62	0.33
-336	0.61	0.33
-335	0.59	0.32
-334	0.58	0.32
-333	0.56	0.32
-332	0.55	0.31
-331	0.54	0.31
-330	0.53	0.31
-329	0.52	0.31
-328	0.51	0.31
-327	0.5	0.31
-326	0.49	0.31
-325	0.49	0.31
-324	0.48	0.31
-323	0.48	0.31
-322	0.47	0.31
-321	0.47	0.31
-320	0.47	0.31
-319	0.46	0.31
-318	0.46	0.32
-317	0.46	0.32
-316	0.46	0.32
-315	0.45	0.32
-314	0.45	0.32
-313	0.45	0.32
-312	0.45	0.32
-311	0.45	0.32
-310	0.45	0.33
-309	0.45	0.33
-308	0.45	0.33
-307	0.45	0.33
-306	0.45	0.33
-305	0.45	0.33
-304	0.45	0.33
-303	0.45	0.34
-302	0.45	0.34
-301	0.45	0.34
-300	0.45	0.34

Crank Angle	Diesel mode	Dual Fuel mode
-299	0.45	0.34
-298	0.45	0.34
-297	0.45	0.35
-296	0.45	0.35
-295	0.45	0.35
-294	0.45	0.35
-293	0.45	0.35
-292	0.45	0.35
-291	0.45	0.35
-290	0.45	0.35
-289	0.46	0.36
-288	0.46	0.36
-287	0.46	0.36
-286	0.46	0.36
-285	0.46	0.36
-284	0.46	0.36
-283	0.46	0.36
-282	0.46	0.36
-281	0.46	0.37
-280	0.47	0.37
-279	0.47	0.37
-278	0.47	0.37
-277	0.47	0.37
-276	0.47	0.37
-275	0.47	0.37
-274	0.48	0.38
-273	0.48	0.38
-272	0.48	0.38
-271	0.48	0.38
-270	0.49	0.38
-269	0.49	0.38
-268	0.49	0.39
-267	0.49	0.39
-266	0.5	0.39
-265	0.5	0.39
-264	0.5	0.39
-263	0.5	0.39
-262	0.51	0.4
-261	0.51	0.4
-260	0.51	0.4
-259	0.52	0.4
-258	0.52	0.4
-257	0.52	0.4

Crank Angle	Diesel mode	Dual Fuel mode
-256	0.53	0.41
-255	0.53	0.41
-254	0.53	0.41
-253	0.54	0.41
-252	0.54	0.41
-251	0.54	0.41
-250	0.55	0.42
-249	0.55	0.42
-248	0.55	0.42
-247	0.56	0.42
-246	0.56	0.42
-245	0.56	0.42
-244	0.57	0.43
-243	0.57	0.43
-242	0.57	0.43
-241	0.58	0.43
-240	0.58	0.43
-239	0.59	0.44
-238	0.59	0.44
-237	0.59	0.44
-236	0.6	0.44
-235	0.6	0.45
-234	0.6	0.45
-233	0.61	0.45
-232	0.61	0.45
-231	0.62	0.46
-230	0.62	0.46
-229	0.62	0.46
-228	0.63	0.46
-227	0.63	0.47
-226	0.64	0.47
-225	0.64	0.47
-224	0.64	0.48
-223	0.65	0.48
-222	0.65	0.48
-221	0.66	0.49
-220	0.66	0.49
-219	0.66	0.49
-218	0.67	0.5
-217	0.67	0.5
-216	0.68	0.5
-215	0.68	0.51
-214	0.69	0.51

Crank Angle	Diesel mode	Dual Fuel mode
-213	0.69	0.51
-212	0.69	0.52
-211	0.7	0.52
-210	0.7	0.53
-209	0.71	0.53
-208	0.71	0.53
-207	0.71	0.54
-206	0.72	0.54
-205	0.72	0.54
-204	0.73	0.55
-203	0.73	0.55
-202	0.73	0.56
-201	0.74	0.56
-200	0.74	0.57
-199	0.75	0.57
-198	0.75	0.57
-197	0.75	0.58
-196	0.76	0.58
-195	0.76	0.59
-194	0.77	0.59
-193	0.77	0.6
-192	0.77	0.6
-191	0.78	0.61
-190	0.78	0.61
-189	0.79	0.62
-188	0.79	0.62
-187	0.79	0.63
-186	0.8	0.63
-185	0.8	0.64
-184	0.81	0.64
-183	0.81	0.65
-182	0.81	0.66
-181	0.82	0.66
-180	0.82	0.67
-179	0.83	0.67
-178	0.83	0.68
-177	0.83	0.69
-176	0.84	0.69
-175	0.84	0.7
-174	0.85	0.7
-173	0.85	0.71
-172	0.86	0.72
-171	0.86	0.72

Crank Angle	Diesel mode	Dual Fuel mode
-170	0.86	0.73
-169	0.87	0.73
-168	0.87	0.74
-167	0.88	0.75
-166	0.88	0.75
-165	0.89	0.76
-164	0.89	0.77
-163	0.9	0.77
-162	0.91	0.78
-161	0.91	0.79
-160	0.92	0.79
-159	0.92	0.8
-158	0.93	0.81
-157	0.94	0.81
-156	0.94	0.82
-155	0.95	0.83
-154	0.96	0.83
-153	0.96	0.84
-152	0.97	0.85
-151	0.98	0.86
-150	0.99	0.86
-149	0.99	0.87
-148	1	0.88
-147	1.01	0.89
-146	1.02	0.89
-145	1.03	0.9
-144	1.04	0.91
-143	1.05	0.92
-142	1.06	0.93
-141	1.07	0.94
-140	1.08	0.95
-139	1.09	0.96
-138	1.1	0.97
-137	1.11	0.98
-136	1.12	0.99
-135	1.13	1
-134	1.14	1.01
-133	1.15	1.02
-132	1.17	1.04
-131	1.18	1.05
-130	1.19	1.06
-129	1.2	1.07
-128	1.21	1.09

Crank Angle	Diesel mode	Dual Fuel mode
-127	1.23	1.1
-126	1.24	1.11
-125	1.25	1.13
-124	1.26	1.14
-123	1.28	1.16
-122	1.29	1.17
-121	1.3	1.19
-120	1.32	1.2
-119	1.33	1.22
-118	1.34	1.23
-117	1.36	1.25
-116	1.37	1.27
-115	1.39	1.28
-114	1.4	1.3
-113	1.42	1.32
-112	1.43	1.34
-111	1.45	1.35
-110	1.46	1.37
-109	1.48	1.39
-108	1.5	1.41
-107	1.52	1.43
-106	1.53	1.45
-105	1.55	1.47
-104	1.57	1.49
-103	1.59	1.51
-102	1.61	1.54
-101	1.64	1.56
-100	1.66	1.58
-99	1.68	1.61
-98	1.71	1.63
-97	1.73	1.66
-96	1.76	1.68
-95	1.78	1.71
-94	1.81	1.74
-93	1.84	1.77
-92	1.87	1.8
-91	1.9	1.83
-90	1.94	1.86
-89	1.97	1.89
-88	2.01	1.93
-87	2.04	1.96
-86	2.08	2
-85	2.12	2.04

Crank Angle	Diesel mode	Dual Fuel mode
-84	2.16	2.08
-83	2.21	2.12
-82	2.25	2.16
-81	2.3	2.2
-80	2.35	2.25
-79	2.4	2.29
-78	2.45	2.34
-77	2.51	2.39
-76	2.56	2.44
-75	2.62	2.49
-74	2.68	2.55
-73	2.75	2.6
-72	2.82	2.66
-71	2.89	2.72
-70	2.96	2.79
-69	3.03	2.86
-68	3.11	2.93
-67	3.19	3
-66	3.27	3.08
-65	3.36	3.16
-64	3.45	3.25
-63	3.54	3.34
-62	3.64	3.43
-61	3.74	3.54
-60	3.85	3.64
-59	3.95	3.76
-58	4.07	3.88
-57	4.18	4
-56	4.31	4.13
-55	4.44	4.27
-54	4.57	4.41
-53	4.71	4.56
-52	4.86	4.71
-51	5.01	4.87
-50	5.17	5.04
-49	5.34	5.21
-48	5.51	5.4
-47	5.69	5.59
-46	5.88	5.79
-45	6.08	6.01
-44	6.29	6.23
-43	6.51	6.46
-42	6.74	6.7

Crank Angle	Diesel mode	Dual Fuel mode	Crank Angle	Diesel mode	Dual Fuel mode
-41	6.99	6.95	2	34.79	33.28
-40	7.26	7.22	3	35.42	33.59
-39	7.55	7.5	4	36.36	33.97
-38	7.86	7.8	5	37.69	34.61
-37	8.18	8.11	6	39.29	35.78
-36	8.53	8.45	7	40.83	37.79
-35	8.89	8.8	8	41.96	40.64
-34	9.27	9.18	9	42.53	43.81
-33	9.67	9.58	10	42.63	46.51
-32	10.09	10	11	42.38	48.22
-31	10.53	10.44	12	41.87	49.08
-30	11	10.91	13	41.18	49.3
-29	11.49	11.4	14	40.36	49.09
-28	12.01	11.92	15	39.44	48.58
-27	12.57	12.48	16	38.45	47.86
-26	13.15	13.07	17	37.41	47
-25	13.78	13.7	18	36.34	46.03
-24	14.43	14.36	19	35.24	44.98
-23	15.12	15.05	20	34.12	43.87
-22	15.84	15.77	21	32.98	42.71
-21	16.58	16.51	22	31.83	41.51
-20	17.35	17.27	23	30.67	40.29
-19	18.14	18.05	24	29.5	39.03
-18	18.96	18.85	25	28.34	37.76
-17	19.8	19.66	26	27.18	36.48
-16	20.66	20.49	27	26.05	35.19
-15	21.54	21.32	28	24.93	33.89
-14	22.44	22.17	29	23.85	32.61
-13	23.36	23.03	30	22.8	31.35
-12	24.29	23.91	31	21.78	30.12
-11	25.23	24.79	32	20.81	28.92
-10	26.17	25.69	33	19.86	27.77
-9	27.12	26.59	34	18.96	26.65
-8	28.04	27.48	35	18.09	25.58
-7	28.94	28.32	36	17.25	24.56
-6	29.8	29.11	37	16.46	23.57
-5	30.62	29.84	38	15.7	22.63
-4	31.39	30.52	39	14.97	21.72
-3	32.1	31.14	40	14.28	20.86
-2	32.75	31.71	41	13.63	20.03
-1	33.33	32.21	42	13.01	19.24
0	33.85	32.63	43	12.42	18.48
1	34.31	32.98	44	11.86	17.76

Crank Angle	Diesel mode	Dual Fuel mode
45	11.33	17.07
46	10.83	16.41
47	10.36	15.78
48	9.9	15.17
49	9.47	14.59
50	9.06	14.04
51	8.67	13.51
52	8.29	13.01
53	7.94	12.53
54	7.6	12.07
55	7.27	11.63
56	6.96	11.22
57	6.67	10.83
58	6.39	10.45
59	6.12	10.1
60	5.87	9.76
61	5.64	9.43
62	5.42	9.12
63	5.21	8.82
64	5.01	8.53
65	4.82	8.25
66	4.64	7.99
67	4.46	7.73
68	4.3	7.49
69	4.13	7.26
70	3.98	7.05
71	3.83	6.84
72	3.69	6.64
73	3.55	6.45
74	3.42	6.26
75	3.3	6.09
76	3.18	5.92
77	3.06	5.76
78	2.95	5.6
79	2.85	5.45
80	2.75	5.3
81	2.65	5.16
82	2.56	5.02
83	2.47	4.89
84	2.38	4.77
85	2.3	4.64
86	2.22	4.53
87	2.15	4.41

Crank Angle	Diesel mode	Dual Fuel mode
88	2.08	4.3
89	2.01	4.19
90	1.94	4.09
91	1.88	3.99
92	1.82	3.89
93	1.76	3.8
94	1.71	3.71
95	1.66	3.62
96	1.61	3.54
97	1.56	3.46
98	1.51	3.38
99	1.47	3.31
100	1.42	3.24
101	1.38	3.17
102	1.34	3.1
103	1.31	3.03
104	1.27	2.97
105	1.24	2.91
106	1.2	2.85
107	1.17	2.8
108	1.14	2.74
109	1.11	2.69
110	1.08	2.64
111	1.05	2.59
112	1.03	2.54
113	1	2.5
114	0.98	2.45
115	0.95	2.41
116	0.93	2.37
117	0.91	2.33
118	0.89	2.29
119	0.87	2.26
120	0.85	2.22
121	0.83	2.19
122	0.82	2.16
123	0.8	2.13
124	0.78	2.09
125	0.77	2.07
126	0.75	2.04
127	0.74	2.01
128	0.72	1.98
129	0.71	1.96
130	0.69	1.93

Crank Angle	Diesel mode	Dual Fuel mode
131	0.68	1.91
132	0.66	1.89
133	0.65	1.86
134	0.64	1.84
135	0.62	1.82
136	0.61	1.8
137	0.6	1.77
138	0.59	1.75
139	0.58	1.73
140	0.56	1.71
141	0.55	1.69
142	0.54	1.67
143	0.53	1.65
144	0.52	1.64
145	0.51	1.62
146	0.5	1.6
147	0.49	1.58
148	0.48	1.57
149	0.47	1.55
150	0.47	1.53
151	0.46	1.52
152	0.45	1.5
153	0.44	1.48
154	0.43	1.47
155	0.43	1.45
156	0.42	1.44
157	0.41	1.42
158	0.4	1.41
159	0.4	1.39
160	0.39	1.38
161	0.38	1.37
162	0.38	1.35
163	0.37	1.34
164	0.37	1.32
165	0.36	1.31
166	0.36	1.3
167	0.35	1.28
168	0.35	1.27
169	0.34	1.26
170	0.34	1.25
171	0.33	1.23
172	0.33	1.22
173	0.33	1.21

Crank Angle	Diesel mode	Dual Fuel mode
174	0.32	1.2
175	0.32	1.19
176	0.32	1.18
177	0.31	1.16
178	0.31	1.15
179	0.31	1.14
180	0.3	1.13
181	0.3	1.11
182	0.3	1.1
183	0.3	1.09
184	0.29	1.07
185	0.29	1.06
186	0.29	1.05
187	0.29	1.03
188	0.28	1.02
189	0.28	1
190	0.28	0.99
191	0.28	0.97
192	0.28	0.95
193	0.27	0.94
194	0.27	0.92
195	0.27	0.9
196	0.27	0.88
197	0.27	0.86
198	0.27	0.85
199	0.26	0.83
200	0.26	0.81
201	0.26	0.79
202	0.26	0.77
203	0.26	0.75
204	0.25	0.73
205	0.25	0.7
206	0.25	0.68
207	0.25	0.66
208	0.25	0.64
209	0.24	0.62
210	0.24	0.59
211	0.24	0.57
212	0.24	0.55
213	0.23	0.53
214	0.23	0.5
215	0.23	0.48
216	0.23	0.46

Crank Angle	Diesel mode	Dual Fuel mode
217	0.22	0.44
218	0.22	0.42
219	0.22	0.4
220	0.22	0.38
221	0.21	0.36
222	0.21	0.34
223	0.21	0.33
224	0.21	0.31
225	0.21	0.29
226	0.2	0.28
227	0.2	0.26
228	0.2	0.25
229	0.2	0.23
230	0.2	0.22
231	0.2	0.21
232	0.2	0.2
233	0.2	0.19
234	0.2	0.18
235	0.2	0.17
236	0.2	0.17
237	0.2	0.16
238	0.2	0.15
239	0.2	0.15
240	0.2	0.15
241	0.2	0.15
242	0.2	0.15
243	0.2	0.15
244	0.21	0.15
245	0.21	0.15
246	0.21	0.15
247	0.22	0.15
248	0.22	0.16
249	0.22	0.16
250	0.23	0.16
251	0.23	0.17
252	0.24	0.17
253	0.24	0.18
254	0.25	0.18
255	0.25	0.19
256	0.26	0.19
257	0.26	0.2
258	0.27	0.2
259	0.27	0.21

Crank Angle	Diesel mode	Dual Fuel mode
260	0.28	0.21
261	0.28	0.22
262	0.29	0.23
263	0.3	0.23
264	0.3	0.24
265	0.31	0.24
266	0.31	0.25
267	0.32	0.25
268	0.33	0.26
269	0.33	0.26
270	0.34	0.27
271	0.35	0.27
272	0.35	0.28
273	0.36	0.28
274	0.37	0.29
275	0.37	0.29
276	0.38	0.29
277	0.39	0.3
278	0.4	0.3
279	0.4	0.3
280	0.41	0.31
281	0.42	0.31
282	0.42	0.31
283	0.43	0.31
284	0.44	0.32
285	0.45	0.32
286	0.45	0.32
287	0.46	0.32
288	0.47	0.32
289	0.48	0.32
290	0.48	0.32
291	0.49	0.32
292	0.5	0.32
293	0.5	0.32
294	0.51	0.32
295	0.52	0.32
296	0.52	0.32
297	0.53	0.32
298	0.54	0.32
299	0.54	0.32
300	0.55	0.31
301	0.56	0.31
302	0.56	0.31

Crank Angle	Diesel mode	Dual Fuel mode
303	0.57	0.31
304	0.57	0.3
305	0.58	0.3
306	0.58	0.3
307	0.59	0.3
308	0.59	0.29
309	0.6	0.29
310	0.6	0.29
311	0.6	0.29
312	0.61	0.28
313	0.61	0.28
314	0.62	0.28
315	0.62	0.27
316	0.62	0.27
317	0.63	0.27
318	0.63	0.26
319	0.63	0.26
320	0.64	0.26
321	0.64	0.25
322	0.64	0.25
323	0.65	0.25
324	0.65	0.25
325	0.66	0.24
326	0.66	0.24
327	0.67	0.24
328	0.67	0.24
329	0.67	0.24
330	0.68	0.24
331	0.68	0.24
332	0.69	0.24
333	0.69	0.24
334	0.7	0.24
335	0.7	0.25
336	0.7	0.25
337	0.71	0.25
338	0.71	0.25
339	0.71	0.25
340	0.72	0.25
341	0.72	0.26
342	0.72	0.26
343	0.73	0.26
344	0.73	0.27
345	0.74	0.27

Crank Angle	Diesel mode	Dual Fuel mode
346	0.75	0.28
347	0.76	0.29
348	0.76	0.29
349	0.78	0.3
350	0.79	0.31
351	0.8	0.32
352	0.81	0.32
353	0.83	0.33
354	0.84	0.34
355	0.85	0.35
356	0.85	0.36
357	0.82	0.34
358	0.67	0.28
359	0.43	0.18

Table 22 Mean gas temperature with respect to crank angle in diesel and dual fuel mode

Crank angle	Diesel mode	Dual fuel mode
-360	11.7	13.89
-359	11.75	13.97
-358	11.83	14.07
-357	11.93	14.17
-356	12.05	14.27
-355	12.2	14.37
-354	12.37	14.46
-353	12.56	14.54
-352	12.79	14.62
-351	13.03	14.69
-350	13.31	14.76
-349	13.6	14.82
-348	13.92	14.88
-347	14.27	14.92
-346	14.64	14.96
-345	15.04	14.98
-344	15.46	15
-343	15.91	15
-342	16.4	15
-341	16.91	14.98
-340	17.45	14.96
-339	18.02	14.93
-338	18.62	14.9
-337	19.24	14.87
-336	19.89	14.84
-335	20.56	14.82
-334	21.26	14.81
-333	21.99	14.82
-332	22.74	14.84
-331	23.52	14.89
-330	24.32	14.97
-329	25.16	15.07
-328	26.02	15.2
-327	26.9	15.37
-326	27.81	15.57
-325	28.75	15.81
-324	29.7	16.09
-323	30.68	16.4
-322	31.67	16.75
-321	32.68	17.12
-320	33.71	17.52
-319	34.76	17.95
-318	35.82	18.39
-317	36.9	18.85
-316	38	19.32
-315	39.11	19.81
-314	40.24	20.31
-313	41.39	20.82
-312	42.54	21.35
-311	43.71	21.9
-310	44.89	22.47
-309	46.09	23.06
-308	47.3	23.67
-307	48.52	24.3
-306	49.75	24.94
-305	51	25.6
-304	52.25	26.28
-303	53.52	26.97
-302	54.8	27.68
-301	56.09	28.41
-300	57.39	29.15
-299	58.7	29.9
-298	60.01	30.66
-297	61.34	31.43
-296	62.66	32.2
-295	64	32.98
-294	65.35	33.75

Crank angle	Diesel mode	Dual fuel mode
-293	66.7	34.52
-292	68.06	35.29
-291	69.43	36.06
-290	70.81	36.84
-289	72.2	37.61
-288	73.6	38.38
-287	75.02	39.16
-286	76.42	39.94
-285	77.84	40.74
-284	79.27	41.54
-283	80.74	42.35
-282	82.19	43.18
-281	83.65	44.02
-280	85.12	44.88
-279	86.6	45.76
-278	88.09	46.66
-277	89.59	47.58
-276	91.09	48.52
-275	92.6	49.49
-274	94.12	50.47
-273	95.64	51.48
-272	97.17	52.51
-271	98.71	53.56
-270	100.25	54.62
-269	101.8	55.71
-268	103.35	56.81
-267	104.91	57.93
-266	106.48	59.06
-265	108.05	60.22
-264	109.62	61.38
-263	111.19	62.57
-262	112.77	63.77
-261	114.36	64.98
-260	115.95	66.22
-259	117.54	67.46

Crank angle	Diesel mode	Dual fuel mode
-258	119.06	68.73
-257	120.6	70.01
-256	122.13	71.31
-255	123.83	72.62
-254	125.37	73.95
-253	126.93	75.31
-252	128.48	76.67
-251	130.02	78.06
-250	131.55	79.47
-249	133.08	80.89
-248	134.6	82.32
-247	136.11	83.77
-246	137.62	85.22
-245	139.11	86.69
-244	140.6	88.16
-243	142.07	89.63
-242	143.54	91.11
-241	144.99	92.66
-240	146.43	94.22
-239	147.86	95.79
-238	149.29	97.22
-237	150.69	98.77
-236	152.09	100.33
-235	153.47	101.9
-234	154.84	103.47
-233	156.19	105.06
-232	157.53	106.65
-231	158.84	108.24
-230	160.13	109.85
-229	161.4	111.45
-228	162.65	113.06
-227	163.89	114.67
-226	165.13	116.29
-225	166.31	117.9
-224	167.38	119.51

Crank angle	Diesel mode	Dual fuel mode
-223	168.4	121.11
-222	169.46	122.71
-221	170.59	124.31
-220	171.71	125.89
-219	172.77	127.46
-218	173.78	129.03
-217	174.75	130.58
-216	175.7	132.12
-215	176.63	133.65
-214	177.53	135.17
-213	178.42	136.67
-212	179.28	138.17
-211	180.11	139.65
-210	180.93	141.12
-209	181.71	142.58
-208	182.45	144.02
-207	183.16	145.43
-206	183.82	146.83
-205	184.44	148.21
-204	185.01	149.56
-203	185.55	150.89
-202	186.05	152.2
-201	186.51	153.49
-200	186.93	154.75
-199	187.32	155.99
-198	187.68	157.2
-197	188.02	158.4
-196	188.34	159.56
-195	188.65	160.71
-194	188.95	161.82
-193	189.24	162.92
-192	189.53	163.99
-191	189.82	165.05
-190	190.13	166.08
-189	190.45	167.09

Crank angle	Diesel mode	Dual fuel mode
-188	190.77	168.09
-187	191.1	169.06
-186	191.44	170.01
-185	191.78	170.94
-184	192.13	171.87
-183	192.49	172.77
-182	192.87	173.67
-181	193.25	174.55
-180	193.65	175.43
-179	194.06	176.3
-178	194.49	177.16
-177	194.93	178.02
-176	195.38	178.87
-175	195.85	179.71
-174	196.32	180.55
-173	196.81	181.39
-172	197.31	182.24
-171	197.82	183.1
-170	198.34	183.97
-169	198.87	184.83
-168	199.39	185.69
-167	199.92	186.54
-166	200.45	187.38
-165	200.98	188.19
-164	201.52	188.98
-163	202.07	189.75
-162	202.63	190.49
-161	203.2	191.22
-160	203.77	191.95
-159	204.36	192.69
-158	204.95	193.44
-157	205.56	194.2
-156	206.18	194.97
-155	206.81	195.76
-154	207.45	196.57

Crank angle	Diesel mode	Dual fuel mode
-153	208.09	197.39
-152	208.73	198.24
-151	209.38	199.09
-150	210.02	199.97
-149	210.66	200.85
-148	211.3	201.76
-147	211.94	202.68
-146	212.57	203.63
-145	213.2	204.6
-144	213.83	205.6
-143	214.45	206.62
-142	215.06	207.66
-141	215.68	208.71
-140	216.3	209.77
-139	216.94	210.85
-138	217.61	211.93
-137	218.31	213.03
-136	219.05	214.15
-135	219.85	215.32
-134	220.7	216.53
-133	221.59	217.81
-132	222.51	219.15
-131	223.45	220.56
-130	224.42	222.02
-129	225.39	223.52
-128	226.37	225.05
-127	227.34	226.6
-126	228.29	228.16
-125	229.23	229.74
-124	230.13	231.33
-123	231.01	232.94
-122	231.87	234.55
-121	232.71	236.19
-120	233.55	237.83
-119	234.38	239.47

Crank angle	Diesel mode	Dual fuel mode
-118	235.22	241.13
-117	236.07	242.79
-116	236.9	244.45
-115	237.74	246.1
-114	238.63	247.72
-113	239.59	249.32
-112	240.59	250.94
-111	241.63	252.63
-110	242.72	254.35
-109	243.88	256.03
-108	245.12	257.65
-107	246.45	259.28
-106	247.87	260.96
-105	249.37	262.68
-104	250.96	264.41
-103	252.64	266.15
-102	254.37	267.88
-101	256.17	269.61
-100	258	271.36
-99	259.88	273.13
-98	261.78	274.95
-97	263.71	276.82
-96	265.66	278.74
-95	267.64	280.69
-94	269.64	282.66
-93	271.63	284.65
-92	273.62	286.63
-91	275.57	288.61
-90	277.49	290.58
-89	279.36	292.53
-88	281.21	294.45
-87	283.04	296.35
-86	284.86	298.23
-85	286.69	300.08
-84	288.52	301.92

Crank angle	Diesel mode	Dual fuel mode
-83	290.34	303.75
-82	292.15	305.56
-81	293.94	307.34
-80	295.72	309.08
-79	297.48	310.8
-78	299.21	312.5
-77	300.91	314.2
-76	302.6	315.91
-75	304.31	317.63
-74	306.02	319.36
-73	307.72	321.1
-72	309.39	322.87
-71	311.01	324.68
-70	312.57	326.55
-69	314.08	328.45
-68	315.57	330.38
-67	317.03	332.32
-66	318.49	334.3
-65	319.97	336.34
-64	321.5	338.46
-63	323.07	340.65
-62	324.69	342.91
-61	326.35	345.24
-60	328.05	347.62
-59	329.79	350.02
-58	331.57	352.41
-57	333.43	354.76
-56	335.36	357.06
-55	337.39	359.29
-54	339.51	361.45
-53	341.71	363.55
-52	343.96	365.65
-51	346.23	367.77
-50	348.47	369.97
-49	350.63	372.26

Crank angle	Diesel mode	Dual fuel mode
-48	352.71	374.66
-47	354.71	377.2
-46	356.65	379.9
-45	358.57	382.79
-44	360.54	385.83
-43	362.62	388.99
-42	364.86	392.24
-41	367.3	395.55
-40	369.92	398.92
-39	372.69	402.31
-38	375.59	405.7
-37	378.57	409.04
-36	381.58	412.3
-35	384.58	415.5
-34	387.54	418.68
-33	390.49	421.94
-32	393.45	425.35
-31	396.47	428.97
-30	399.59	432.81
-29	402.86	436.91
-28	406.34	441.27
-27	410.03	445.9
-26	413.91	450.76
-25	417.94	455.75
-24	422.08	460.76
-23	426.3	465.73
-22	430.57	470.6
-21	434.83	475.38
-20	439.06	480.07
-19	443.21	484.68
-18	447.31	489.26
-17	451.44	493.88
-16	455.66	498.61
-15	460.06	503.53
-14	464.65	508.64

Crank angle	Diesel mode	Dual fuel mode
-13	469.46	513.95
-12	474.49	519.46
-11	479.77	525.18
-10	485.29	531.12
-9	491.06	537.28
-8	497.07	543.61
-7	503.35	550.03
-6	509.93	556.56
-5	516.79	563.23
-4	523.85	570.13
-3	530.93	577.34
-2	537.86	584.95
-1	544.47	593.12
0	550.69	602.16
1	556.51	612.57
2	561.92	625.52
3	566.89	643.17
4	571.32	667.84
5	575.09	699.96
6	578.11	736.66
7	580.36	772.55
8	581.81	802.82
9	582.52	826.02
10	582.56	843.02
11	582.05	855.51
12	581.09	864.56
13	579.73	871.37
14	577.91	876.41
15	575.5	880.2
16	572.42	882.93
17	568.6	884.72
18	564.03	885.59
19	558.72	885.48
20	552.68	884.31
21	545.91	881.98

Crank angle	Diesel mode	Dual fuel mode
22	538.48	878.41
23	530.5	873.55
24	522.12	867.46
25	513.44	860.22
26	504.54	852.03
27	495.47	843.04
28	486.24	833.44
29	476.89	823.34
30	467.46	812.86
31	458	802.1
32	448.53	791.11
33	439.12	779.92
34	429.79	768.55
35	420.6	757.05
36	411.56	745.37
37	402.69	733.54
38	393.97	721.6
39	385.39	709.57
40	376.92	697.52
41	368.51	685.47
42	360.14	673.48
43	351.78	661.6
44	343.45	649.88
45	335.17	638.38
46	326.97	627.16
47	318.89	616.19
48	310.96	605.42
49	303.24	594.77
50	295.76	584.16
51	288.54	573.53
52	281.58	562.84
53	274.84	552.06
54	268.3	541.21
55	261.96	530.35
56	255.79	519.57

Crank angle	Diesel mode	Dual fuel mode
57	249.78	508.97
58	243.93	498.6
59	238.23	488.54
60	232.71	478.78
61	227.36	469.32
62	222.19	460.12
63	217.21	451.16
64	212.41	442.38
65	207.78	433.77
66	203.32	425.3
67	199.02	416.97
68	194.87	408.78
69	190.87	400.75
70	187.02	392.87
71	183.29	385.16
72	179.67	377.59
73	176.14	370.16
74	172.7	362.83
75	169.34	355.59
76	166.06	348.44
77	162.84	341.37
78	159.65	334.36
79	156.5	327.41
80	153.37	320.53
81	150.26	313.71
82	147.16	306.96
83	144.08	300.29
84	141	293.69
85	137.93	287.18
86	134.86	280.77
87	131.8	274.44
88	128.75	268.22
89	125.72	262.12
90	122.71	256.13
91	119.72	250.25

Crank angle	Diesel mode	Dual fuel mode
92	116.77	244.48
93	113.84	238.82
94	110.94	233.27
95	108.07	227.85
96	105.23	222.57
97	102.42	217.44
98	99.65	212.45
99	96.91	207.59
100	94.2	202.8
101	91.53	198.13
102	88.89	193.56
103	86.3	189.2
104	83.73	184.86
105	81.21	180.61
106	78.72	176.45
107	76.26	172.4
108	73.84	168.44
109	71.46	164.58
110	69.12	160.81
111	66.83	157.14
112	64.59	153.54
113	62.4	150.01
114	60.26	146.56
115	58.15	143.18
116	56.08	139.87
117	54.03	136.63
118	52	133.45
119	50	130.33
120	48.01	127.26
121	46.05	124.22
122	44.13	121.22
123	42.26	118.24
124	40.44	115.27
125	38.69	112.31
126	37.01	109.36

Crank angle	Diesel mode	Dual fuel mode
127	35.4	106.4
128	33.87	103.46
129	32.41	100.53
130	31.04	97.63
131	29.75	94.77
132	28.55	91.95
133	27.44	89.18
134	26.43	86.45
135	25.51	83.78
136	24.69	81.16
137	23.95	78.58
138	23.29	76.07
139	22.72	73.6
140	22.23	71.18
141	21.82	68.82
142	21.49	66.51
143	21.24	64.26
144	21.05	62.06
145	20.94	59.92
146	20.9	57.83
147	20.92	55.79
148	21	53.82
149	21.15	51.9
150	21.35	50.06
151	21.61	48.27
152	21.93	46.55
153	22.32	44.9
154	22.77	43.32
155	23.28	41.81
156	23.85	40.36
157	24.47	38.99
158	25.16	37.68
159	25.91	36.43
160	26.7	35.25
161	27.55	34.13

Crank angle	Diesel mode	Dual fuel mode
162	28.44	33.07
163	29.37	32.08
164	30.34	31.14
165	31.34	30.27
166	32.36	29.46
167	33.41	28.7
168	34.48	27.99
169	35.57	27.34
170	36.68	26.73
171	37.81	26.17
172	38.97	25.65
173	40.17	25.18
174	41.39	24.73
175	42.65	24.33
176	43.92	23.95
177	45.22	23.62
178	46.53	23.32
179	47.87	23.06
180	49.23	22.83
181	50.61	22.63
182	52.01	22.47
183	53.44	22.33
184	54.89	22.21
185	56.36	22.13
186	57.84	22.06
187	59.33	22.02
188	60.8	22.01
189	62.26	22.02
190	63.71	22.06
191	65.13	22.14
192	66.54	22.24
193	67.92	22.36
194	69.29	22.5
195	70.63	22.65
196	71.94	22.81

Crank angle	Diesel mode	Dual fuel mode
197	73.23	22.96
198	74.5	23.12
199	75.74	23.27
200	76.96	23.42
201	78.15	23.57
202	79.3	23.71
203	80.43	23.85
204	81.53	23.98
205	82.59	24.11
206	83.62	24.23
207	84.62	24.36
208	85.6	24.47
209	86.56	24.58
210	87.49	24.69
211	88.4	24.8
212	89.28	24.91
213	90.14	25.01
214	90.96	25.13
215	91.74	25.24
216	92.49	25.37
217	93.19	25.51
218	93.85	25.65
219	94.47	25.81
220	95.05	25.99
221	95.6	26.18
222	96.12	26.39
223	96.6	26.62
224	97.05	26.86
225	97.48	27.11
226	97.87	27.37
227	98.23	27.64
228	98.55	27.92
229	98.85	28.2
230	99.12	28.48
231	99.37	28.77

Crank angle	Diesel mode	Dual fuel mode
232	99.61	29.07
233	99.83	29.38
234	100.04	29.7
235	100.22	30.03
236	100.38	30.38
237	100.52	30.74
238	100.63	31.11
239	100.72	31.5
240	100.78	31.9
241	100.82	32.32
242	100.83	32.76
243	100.82	33.21
244	100.78	33.67
245	100.72	34.16
246	100.61	34.66
247	100.47	35.18
248	100.29	35.71
249	100.06	36.25
250	99.79	36.79
251	99.48	37.32
252	99.13	37.86
253	98.75	38.38
254	98.34	38.9
255	97.89	39.42
256	97.42	39.92
257	96.91	40.41
258	96.37	40.89
259	95.8	41.36
260	95.19	41.81
261	94.56	42.24
262	93.9	42.67
263	93.21	43.07
264	92.5	43.46
265	91.77	43.83
266	91.01	44.19

Crank angle	Diesel mode	Dual fuel mode
267	90.23	44.53
268	89.42	44.86
269	88.58	45.16
270	87.73	45.45
271	86.84	45.72
272	85.94	45.97
273	85.01	46.2
274	84.07	46.41
275	83.11	46.6
276	82.13	46.77
277	81.13	46.91
278	80.11	47.03
279	79.08	47.12
280	78.04	47.19
281	76.99	47.22
282	75.92	47.23
283	74.84	47.21
284	73.75	47.16
285	72.65	47.07
286	71.54	46.96
287	70.42	46.82
288	69.28	46.64
289	68.14	46.44
290	66.99	46.2
291	65.83	45.93
292	64.67	45.62
293	63.49	45.29
294	62.31	44.92
295	61.13	44.53
296	59.94	44.1
297	58.74	43.64
298	57.55	43.15
299	56.35	42.63
300	55.15	42.08
301	53.95	41.51

Crank angle	Diesel mode	Dual fuel mode
302	52.75	40.9
303	51.56	40.28
304	50.36	39.63
305	49.17	38.95
306	47.98	38.26
307	46.8	37.54
308	45.62	36.8
309	44.45	36.04
310	43.28	35.26
311	42.12	34.47
312	40.97	33.67
313	39.82	32.86
314	38.69	32.04
315	37.57	31.23
316	36.47	30.41
317	35.38	29.61
318	34.31	28.82
319	33.26	28.04
320	32.23	27.27
321	31.23	26.52
322	30.25	25.79
323	29.29	25.07
324	28.35	24.37
325	27.43	23.69
326	26.53	23.02
327	25.66	22.37
328	24.81	21.74
329	23.98	21.12
330	23.17	20.52
331	22.38	19.92
332	21.62	19.34
333	20.88	18.76
334	20.16	18.2
335	19.45	17.64
336	18.77	17.11

Crank angle	Diesel mode	Dual fuel mode
337	18.11	16.59
338	17.48	16.1
339	16.87	15.63
340	16.29	15.2
341	15.74	14.81
342	15.22	14.45
343	14.74	14.13
344	14.3	13.85
345	13.9	13.61
346	13.53	13.4
347	13.19	13.24
348	12.89	13.12
349	12.62	13.03
350	12.39	12.99
351	12.18	12.98
352	12.01	13.01
353	11.87	13.06
354	11.77	13.13
355	11.54	13.05
356	10.84	12.39
357	8.75	10.07
358	5.61	6.47
359	0	0

Table 23 Net heat release with respect to crank angle in diesel and dual fuel mode

Crank angle	Average Cycle	Average Cycle
-360	-0.01	-0.01
-359	0.04	0.04
-358	0.08	0.1
-357	0.09	0.12
-356	0.1	0.14
-355	0.11	0.15
-354	0.12	0.17
-353	0.13	0.19
-352	0.14	0.22
-351	0.16	0.24
-350	0.17	0.26
-349	0.18	0.28
-348	0.19	0.29
-347	0.2	0.3
-346	0.2	0.32
-345	0.21	0.33
-344	0.22	0.33
-343	0.23	0.34
-342	0.24	0.35
-341	0.25	0.37
-340	0.26	0.38
-339	0.28	0.4
-338	0.3	0.42
-337	0.32	0.44
-336	0.34	0.46
-335	0.36	0.49
-334	0.38	0.51
-333	0.4	0.54
-332	0.43	0.58
-331	0.45	0.61
-330	0.48	0.65
-329	0.5	0.68
-328	0.53	0.72
-327	0.56	0.75
-326	0.59	0.79
-325	0.61	0.82
-324	0.63	0.86
-323	0.65	0.88
-322	0.67	0.91
-321	0.69	0.93
-320	0.7	0.95

Crank angle	Average Cycle	Average Cycle
-319	0.72	0.97
-318	0.73	0.99
-317	0.74	1
-316	0.75	1.02
-315	0.77	1.03
-314	0.78	1.05
-313	0.8	1.07
-312	0.81	1.08
-311	0.83	1.1
-310	0.84	1.12
-309	0.86	1.14
-308	0.87	1.16
-307	0.89	1.17
-306	0.9	1.19
-305	0.91	1.21
-304	0.92	1.22
-303	0.94	1.24
-302	0.95	1.25
-301	0.96	1.26
-300	0.96	1.27
-299	0.97	1.28
-298	0.98	1.28
-297	0.98	1.29
-296	0.98	1.29
-295	0.99	1.29
-294	0.99	1.3
-293	0.99	1.3
-292	0.99	1.3
-291	1	1.3
-290	1	1.31
-289	1.01	1.31
-288	1.01	1.32
-287	1.02	1.32
-286	1.02	1.33
-285	1.03	1.33

Crank angle	Average Cycle	Average Cycle
-284	1.04	1.34
-283	1.05	1.35
-282	1.06	1.36
-281	1.07	1.37
-280	1.08	1.38
-279	1.09	1.39
-278	1.1	1.4
-277	1.11	1.41
-276	1.12	1.43
-275	1.13	1.44
-274	1.14	1.45
-273	1.14	1.46
-272	1.15	1.47
-271	1.16	1.48
-270	1.17	1.48
-269	1.17	1.49
-268	1.18	1.49
-267	1.18	1.49
-266	1.19	1.49
-265	1.19	1.5
-264	1.19	1.5
-263	1.2	1.5
-262	1.2	1.5
-261	1.2	1.5
-260	1.21	1.51
-259	1.21	1.51
-258	1.21	1.51
-257	1.22	1.51
-256	1.22	1.51
-255	1.22	1.52
-254	1.23	1.52
-253	1.23	1.52
-252	1.23	1.52
-251	1.24	1.52
-250	1.24	1.52

Crank angle	Average Cycle	Average Cycle
-249	1.24	1.52
-248	1.24	1.51
-247	1.24	1.51
-246	1.24	1.5
-245	1.25	1.49
-244	1.25	1.48
-243	1.25	1.47
-242	1.26	1.46
-241	1.26	1.45
-240	1.26	1.45
-239	1.27	1.44
-238	1.27	1.43
-237	1.27	1.42
-236	1.27	1.42
-235	1.27	1.41
-234	1.27	1.4
-233	1.27	1.4
-232	1.27	1.39
-231	1.26	1.39
-230	1.26	1.38
-229	1.26	1.38
-228	1.25	1.37
-227	1.25	1.36
-226	1.24	1.36
-225	1.24	1.35
-224	1.23	1.33
-223	1.22	1.32
-222	1.22	1.31
-221	1.21	1.29
-220	1.2	1.27
-219	1.19	1.26
-218	1.18	1.24
-217	1.17	1.22
-216	1.16	1.2
-215	1.16	1.19

Crank angle	Average Cycle	Average Cycle
-214	1.15	1.17
-213	1.14	1.15
-212	1.13	1.13
-211	1.11	1.11
-210	1.1	1.09
-209	1.09	1.07
-208	1.08	1.06
-207	1.06	1.04
-206	1.05	1.02
-205	1.04	1.01
-204	1.03	0.99
-203	1.02	0.97
-202	1	0.95
-201	0.99	0.93
-200	0.98	0.9
-199	0.97	0.88
-198	0.95	0.86
-197	0.94	0.83
-196	0.92	0.81
-195	0.91	0.79
-194	0.89	0.77
-193	0.88	0.75
-192	0.86	0.73
-191	0.85	0.72
-190	0.84	0.71
-189	0.82	0.69
-188	0.81	0.68
-187	0.8	0.68
-186	0.78	0.67
-185	0.77	0.66
-184	0.76	0.65
-183	0.74	0.64
-182	0.72	0.64
-181	0.71	0.63
-180	0.69	0.62

Crank angle	Average Cycle	Average Cycle
-179	0.68	0.62
-178	0.67	0.61
-177	0.66	0.6
-176	0.64	0.59
-175	0.63	0.58
-174	0.62	0.57
-173	0.6	0.56
-172	0.59	0.55
-171	0.57	0.54
-170	0.54	0.53
-169	0.52	0.52
-168	0.51	0.52
-167	0.49	0.51
-166	0.47	0.51
-165	0.46	0.51
-164	0.45	0.51
-163	0.44	0.51
-162	0.44	0.52
-161	0.43	0.52
-160	0.43	0.52
-159	0.43	0.52
-158	0.44	0.52
-157	0.44	0.52
-156	0.44	0.52
-155	0.45	0.52
-154	0.45	0.51
-153	0.45	0.5
-152	0.45	0.49
-151	0.45	0.48
-150	0.45	0.47
-149	0.44	0.46
-148	0.43	0.45
-147	0.42	0.44
-146	0.42	0.43
-145	0.41	0.42

Crank angle	Average Cycle	Average Cycle
-144	0.4	0.4
-143	0.4	0.39
-142	0.4	0.38
-141	0.4	0.37
-140	0.4	0.36
-139	0.41	0.36
-138	0.42	0.35
-137	0.43	0.35
-136	0.43	0.35
-135	0.44	0.34
-134	0.45	0.34
-133	0.47	0.32
-132	0.48	0.3
-131	0.48	0.28
-130	0.47	0.25
-129	0.45	0.22
-128	0.43	0.19
-127	0.4	0.16
-126	0.36	0.14
-125	0.33	0.11
-124	0.3	0.08
-123	0.27	0.05
-122	0.24	0.03
-121	0.21	0
-120	0.19	-0.03
-119	0.17	-0.06
-118	0.15	-0.09
-117	0.13	-0.11
-116	0.11	-0.13
-115	0.1	-0.15
-114	0.09	-0.17
-113	0.09	-0.18
-112	0.09	-0.18
-111	0.1	-0.19
-110	0.1	-0.2

Crank angle	Average Cycle	Average Cycle
-109	0.1	-0.22
-108	0.09	-0.23
-107	0.08	-0.25
-106	0.07	-0.26
-105	0.06	-0.28
-104	0.04	-0.3
-103	0.02	-0.31
-102	0.01	-0.29
-101	0	-0.29
-100	-0.01	-0.32
-99	-0.02	-0.32
-98	-0.03	-0.33
-97	-0.05	-0.34
-96	-0.07	-0.36
-95	-0.09	-0.38
-94	-0.11	-0.41
-93	-0.13	-0.43
-92	-0.14	-0.46
-91	-0.15	-0.49
-90	-0.16	-0.52
-89	-0.18	-0.55
-88	-0.21	-0.57
-87	-0.23	-0.58
-86	-0.25	-0.59
-85	-0.27	-0.59
-84	-0.28	-0.6
-83	-0.29	-0.61
-82	-0.3	-0.64
-81	-0.31	-0.65
-80	-0.32	-0.67
-79	-0.33	-0.68
-78	-0.34	-0.68
-77	-0.35	-0.67
-76	-0.36	-0.67
-75	-0.38	-0.66

Crank angle	Average Cycle	Average Cycle
-74	-0.4	-0.64
-73	-0.4	-0.61
-72	-0.4	-0.62
-71	-0.41	-0.66
-70	-0.43	-0.69
-69	-0.46	-0.73
-68	-0.49	-0.75
-67	-0.5	-0.76
-66	-0.52	-0.74
-65	-0.53	-0.71
-64	-0.54	-0.66
-63	-0.54	-0.61
-62	-0.53	-0.58
-61	-0.5	-0.58
-60	-0.48	-0.6
-59	-0.47	-0.65
-58	-0.46	-0.73
-57	-0.46	-0.83
-56	-0.47	-0.94
-55	-0.48	-1.03
-54	-0.51	-1.09
-53	-0.55	-1.12
-52	-0.6	-1.12
-51	-0.65	-1.1
-50	-0.69	-1.05
-49	-0.72	-0.97
-48	-0.72	-0.87
-47	-0.7	-0.77
-46	-0.66	-0.68
-45	-0.59	-0.6
-44	-0.52	-0.52
-43	-0.43	-0.44
-42	-0.33	-0.38
-41	-0.22	-0.34
-40	-0.12	-0.34

Crank angle	Average Cycle	Average Cycle
-39	-0.06	-0.36
-38	-0.03	-0.4
-37	-0.03	-0.44
-36	-0.05	-0.5
-35	-0.07	-0.57
-34	-0.1	-0.61
-33	-0.12	-0.63
-32	-0.12	-0.6
-31	-0.12	-0.52
-30	-0.08	-0.4
-29	-0.03	-0.27
-28	0.04	-0.16
-27	0.08	-0.09
-26	0.07	-0.07
-25	0.03	-0.09
-24	-0.03	-0.13
-23	-0.1	-0.19
-22	-0.16	-0.28
-21	-0.24	-0.38
-20	-0.3	-0.48
-19	-0.33	-0.54
-18	-0.31	-0.53
-17	-0.25	-0.47
-16	-0.16	-0.37
-15	-0.07	-0.26
-14	0.03	-0.1
-13	0.15	0.1
-12	0.29	0.34
-11	0.42	0.61
-10	0.53	0.84
-9	0.62	1.02
-8	0.72	1.17
-7	0.9	1.31
-6	1.18	1.47
-5	1.55	1.61

Crank angle	Average Cycle	Average Cycle
-4	1.97	1.73
-3	2.48	1.83
-2	3.15	1.97
-1	4.12	2.21
0	5.7	2.6
1	8.44	3.14
2	12.56	3.79
3	17.21	4.54
4	20.6	5.41
5	21.2	6.47
6	19.15	7.7
7	15.9	8.97
8	13.07	9.97
9	11.22	10.43
10	10.06	10.34
11	9.43	9.86
12	9.12	9.21
13	9.01	8.59
14	8.96	8.11
15	8.94	7.79
16	8.87	7.56
17	8.72	7.32
18	8.47	7.03
19	8.12	6.69
20	7.69	6.32
21	7.2	5.93
22	6.66	5.52
23	6.13	5.09
24	5.63	4.65
25	5.18	4.22
26	4.76	3.84
27	4.36	3.52
28	3.96	3.24
29	3.58	2.98
30	3.21	2.72

Crank angle	Average Cycle	Average Cycle
31	2.85	2.46
32	2.5	2.2
33	2.15	1.95
34	1.82	1.73
35	1.53	1.54
36	1.28	1.38
37	1.07	1.24
38	0.89	1.11
39	0.72	0.96
40	0.56	0.79
41	0.4	0.62
42	0.26	0.45
43	0.12	0.28
44	-0.01	0.11
45	-0.13	-0.04
46	-0.24	-0.17
47	-0.35	-0.27
48	-0.44	-0.35
49	-0.53	-0.4
50	-0.63	-0.45
51	-0.74	-0.49
52	-0.86	-0.53
53	-0.97	-0.58
54	-1.08	-0.66
55	-1.19	-0.77
56	-1.29	-0.89
57	-1.39	-1.01
58	-1.49	-1.12
59	-1.58	-1.22
60	-1.66	-1.28
61	-1.73	-1.32
62	-1.8	-1.33
63	-1.86	-1.32
64	-1.91	-1.3
65	-1.94	-1.27

Crank angle	Average Cycle	Average Cycle
66	-1.97	-1.25
67	-1.99	-1.24
68	-2	-1.22
69	-1.98	-1.21
70	-1.98	-1.2
71	-1.99	-1.18
72	-1.99	-1.15
73	-1.99	-1.13
74	-1.99	-1.1
75	-1.99	-1.08
76	-1.99	-1.06
77	-1.99	-1.05
78	-1.98	-1.06
79	-1.97	-1.07
80	-1.97	-1.09
81	-1.96	-1.12
82	-1.96	-1.15
83	-1.97	-1.18
84	-1.97	-1.21
85	-1.98	-1.25
86	-1.99	-1.28
87	-2	-1.32
88	-2.01	-1.36
89	-2.02	-1.4
90	-2.02	-1.44
91	-2.03	-1.47
92	-2.04	-1.51
93	-2.04	-1.53
94	-2.05	-1.54
95	-2.05	-1.53
96	-2.05	-1.54
97	-2.05	-1.56
98	-2.05	-1.56
99	-2.04	-1.55
100	-2.03	-1.54

Crank angle	Average Cycle	Average Cycle
101	-2.01	-1.53
102	-1.99	-1.54
103	-1.96	-1.54
104	-1.93	-1.54
105	-1.9	-1.54
106	-1.87	-1.54
107	-1.84	-1.53
108	-1.8	-1.5
109	-1.76	-1.47
110	-1.72	-1.42
111	-1.69	-1.37
112	-1.65	-1.31
113	-1.61	-1.27
114	-1.57	-1.23
115	-1.54	-1.19
116	-1.51	-1.15
117	-1.48	-1.12
118	-1.46	-1.11
119	-1.44	-1.09
120	-1.42	-1.08
121	-1.4	-1.06
122	-1.4	-1.06
123	-1.39	-1.05
124	-1.39	-1.05
125	-1.39	-1.05
126	-1.39	-1.05
127	-1.38	-1.05
128	-1.37	-1.04
129	-1.35	-1.02
130	-1.33	-1.01
131	-1.31	-0.99
132	-1.29	-0.96
133	-1.26	-0.94
134	-1.24	-0.91
135	-1.22	-0.88

Crank angle	Average Cycle	Average Cycle
136	-1.2	-0.85
137	-1.18	-0.81
138	-1.16	-0.78
139	-1.14	-0.75
140	-1.12	-0.71
141	-1.1	-0.68
142	-1.08	-0.64
143	-1.06	-0.61
144	-1.04	-0.57
145	-1.01	-0.54
146	-0.99	-0.51
147	-0.96	-0.47
148	-0.93	-0.44
149	-0.9	-0.41
150	-0.87	-0.38
151	-0.84	-0.34
152	-0.8	-0.31
153	-0.77	-0.28
154	-0.74	-0.24
155	-0.7	-0.21
156	-0.67	-0.18
157	-0.64	-0.15
158	-0.61	-0.11
159	-0.57	-0.08
160	-0.54	-0.05
161	-0.51	-0.02
162	-0.48	0.02
163	-0.45	0.05
164	-0.42	0.08
165	-0.39	0.1
166	-0.36	0.13
167	-0.34	0.15
168	-0.32	0.17
169	-0.29	0.19
170	-0.27	0.21

Crank angle	Average Cycle	Average Cycle
171	-0.25	0.22
172	-0.23	0.24
173	-0.21	0.25
174	-0.2	0.26
175	-0.18	0.27
176	-0.16	0.29
177	-0.14	0.3
178	-0.12	0.31
179	-0.11	0.32
180	-0.09	0.34
181	-0.08	0.35
182	-0.07	0.36
183	-0.06	0.38
184	-0.04	0.39
185	-0.03	0.41
186	-0.01	0.42
187	0.01	0.44
188	0.03	0.45
189	0.05	0.47
190	0.07	0.48
191	0.08	0.49
192	0.1	0.49
193	0.1	0.49
194	0.11	0.49
195	0.11	0.49
196	0.11	0.48
197	0.11	0.47
198	0.12	0.47
199	0.12	0.46
200	0.12	0.45
201	0.12	0.44
202	0.12	0.42
203	0.12	0.41
204	0.12	0.4
205	0.12	0.39

Crank angle	Average Cycle	Average Cycle
206	0.12	0.38
207	0.12	0.36
208	0.12	0.35
209	0.12	0.34
210	0.12	0.32
211	0.12	0.31
212	0.13	0.29
213	0.13	0.28
214	0.14	0.26
215	0.14	0.25
216	0.15	0.24
217	0.15	0.22
218	0.16	0.2
219	0.16	0.17
220	0.16	0.14
221	0.16	0.11
222	0.16	0.1
223	0.16	0.09
224	0.15	0.08
225	0.15	0.06
226	0.16	0.04
227	0.16	0.02
228	0.16	-0.01
229	0.16	-0.03
230	0.16	-0.05
231	0.17	-0.07
232	0.17	-0.09
233	0.18	-0.1
234	0.18	-0.12
235	0.18	-0.14
236	0.19	-0.15
237	0.19	-0.17
238	0.2	-0.19
239	0.2	-0.2
240	0.2	-0.22

Crank angle	Average Cycle	Average Cycle
241	0.2	-0.24
242	0.2	-0.26
243	0.2	-0.28
244	0.19	-0.3
245	0.19	-0.32
246	0.18	-0.34
247	0.17	-0.36
248	0.16	-0.38
249	0.16	-0.4
250	0.15	-0.42
251	0.14	-0.43
252	0.14	-0.45
253	0.13	-0.47
254	0.12	-0.49
255	0.11	-0.51
256	0.1	-0.53
257	0.09	-0.55
258	0.07	-0.57
259	0.06	-0.59
260	0.04	-0.61
261	0.03	-0.62
262	0.01	-0.64
263	-0.01	-0.66
264	-0.03	-0.68
265	-0.04	-0.69
266	-0.07	-0.71
267	-0.09	-0.73
268	-0.11	-0.74
269	-0.14	-0.76
270	-0.14	-0.78
271	-0.1	-0.79
272	-0.07	-0.81
273	-0.14	-0.82
274	-0.3	-0.84
275	-0.41	-0.85

Crank angle	Average Cycle	Average Cycle
276	-0.41	-0.87
277	-0.33	-0.89
278	-0.26	-0.9
279	-0.25	-0.92
280	-0.28	-0.94
281	-0.32	-0.95
282	-0.37	-0.97
283	-0.41	-0.99
284	-0.44	-1.01
285	-0.47	-1.03
286	-0.49	-1.05
287	-0.52	-1.07
288	-0.54	-1.09
289	-0.57	-1.11
290	-0.6	-1.13
291	-0.63	-1.15
292	-0.64	-1.17
293	-0.66	-1.19
294	-0.68	-1.21
295	-0.71	-1.23
296	-0.73	-1.25
297	-0.75	-1.27
298	-0.77	-1.28
299	-0.8	-1.3
300	-0.81	-1.31
301	-0.83	-1.33
302	-0.85	-1.34
303	-0.87	-1.35
304	-0.88	-1.36
305	-0.89	-1.36
306	-0.9	-1.37
307	-0.91	-1.37
308	-0.92	-1.37
309	-0.93	-1.37
310	-0.94	-1.37

Crank angle	Average Cycle	Average Cycle
311	-0.94	-1.37
312	-0.94	-1.37
313	-0.94	-1.36
314	-0.93	-1.34
315	-0.92	-1.33
316	-0.91	-1.31
317	-0.89	-1.29
318	-0.88	-1.26
319	-0.87	-1.24
320	-0.85	-1.21
321	-0.84	-1.19
322	-0.83	-1.16
323	-0.81	-1.14
324	-0.8	-1.11
325	-0.78	-1.09
326	-0.77	-1.07
327	-0.76	-1.05
328	-0.75	-1.03
329	-0.74	-1.01
330	-0.73	-0.99
331	-0.72	-0.97
332	-0.71	-0.96
333	-0.7	-0.93
334	-0.68	-0.91
335	-0.66	-0.88
336	-0.63	-0.84
337	-0.61	-0.81
338	-0.57	-0.76
339	-0.54	-0.72
340	-0.5	-0.67
341	-0.46	-0.63
342	-0.42	-0.58
343	-0.37	-0.52
344	-0.33	-0.47
345	-0.29	-0.41

Crank angle	Average Cycle	Average Cycle
346	-0.25	-0.36
347	-0.21	-0.31
348	-0.17	-0.26
349	-0.14	-0.22
350	-0.11	-0.17
351	-0.08	-0.14
352	-0.05	-0.09
353	-0.07	-0.11
354	-0.28	-0.4
355	-1.18	-1.63
356	-0.13	-0.18
357	-0.09	-0.12
358	-0.04	-0.06
359	0	0