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Energy and Exergy Analysis of I.C. Engines

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--ABSTRACT--

With non-renewable fossil fuel reserves being depleted and in the recent times, there are issues related to their GHG emissions such as, carbon dioxide (CO_2), methane (CH_4), and carbon monoxide (CO), it has become necessity to look forward the use of renewable or inexhaustible fuels to trim down the burden on our non-renewable fuels and for resolving the problem of emissions. Biomass, as a renewable energy source, can either be used directly or converted into other energy products such as biogas. Biogas, a mixture of methane and carbon dioxide with traces of carbon monoxide, hydrogen sulphite, nascent nitrogen and oxygen, is produced from organic wastes in biogas plants under anaerobic conditions is used for power generation. For power generation we need engines. Engines may be of diesel and petrol.Diesel engines contribute an important part of the world's transportation and industrial infrastructure, especially in heavy-duty equipment such as trucks, buses, construction and farm equipments, locomotives, ships etc. However, Biogas does not undergo combustion in compression ignition (CI) engine when used alone due to their low cetane numbers and high auto-ignition temperatures. Hence, the CI engine of the 'dual fuel' approach plays a significant role in the efficient utilization of a wide range of gaseous fuels. During a dual fuel operation, a carbureted air-gas mixture is sucked and compressed like in a conventional diesel engine. The compressed air-gas mixture is fired by a small liquid fuel injection, pilot, which ignites spontaneously at the end of compression process. A diesel engine can be converted easily to a dual function engine with minimum modification with biogas as main fuel and diesel used as pilot fuel contributing 10-20% of total fuel consumption.

The main idea of this work is to carry out energy and exergy analysis of the biogas run dual fuelled diesel engine. The study of this analysis is done by coupling 1st law and 2nd law of thermodynamics. This gives a clear picture on fuel consumption, brake thermal efficiency, exergy efficiency and different availabilities with the varying load and compared to the corresponding diesel values.

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NOMENCLATURE

Abbreviations

GHG	Greenhouse gases
BDC	Bottom Dead Center
BTDC	Before top dead center
BSEC	Brake specific energy consumption
BP	Brake power (kW)
Cc	Cubic centimeter
CH_4	Methane
CI	Compression ignition
CNG	Compressed Natural gas
CO_2	carbon dioxide
CO	Carbon monoxide
H_2s	Hydrogen Sulfide
CR	Compression ratio
LHV	Lower Heating value(MJ/kg)
IC	Internal Combustion
EC	External combustion

SI	Spark Ignition
ICE	Internal combustion Engine
DFT	Dual Fuel Technology
IDI	Indirect injection
IP	Indicated Power(kW)
IT	Injection Timing
J	Joule
K	Kelvin
Kw	Kilo watts
Kj	Kilo Joules
Mm	Milli meter
Min	Minutes
N	Newton
NO_x	Oxides of nitrogen(ppm)
Rpm	Rotation per minute
S	Seconds
Notations	
Q_{in}	Input energy(kW)
P_{shaft}	Shaft energy(kW)
Q_{cw}	Energy transferred to cooling water(kW)
Q_{eg}	Energy transferred to Exhaust gases(kW)
Q_{un}	Uncounted losses(kW)
M'_d	Mass flow rate of diesel in Kg/sec
M'_{pd}	Mass flow rate of pilot fuel(diesel) in Kg/sec
M'_{eg}	Mass flow rate of exhaust gases in Kg/sec
M'_a	Mass flow rate of air in Kg/sec
M'_g	Mass flow rate of biogas in Kg/sec
M'_{we}	Mass flow rate of the cooling water passing through the engine jacket in Kg/sec
M'_{wc}	Mass flow rate of of the cooling water passing through the calorimeter in Kg/sec
T1	Cooling water inlet temperature(K)
T2	Cooling water outlet temperature(K)
T3	Calorimeter water inlet temperature(K)
T4	Calorimeter water outlet temperature(K)
T5	Exhaust gas temperature from Engine(K)
T6	Calorimeter exhaust gas outlet temperature(K)
To	Ambient Temperature(K)
LHV_d	Low heating value of diesel(MJ/kg)
LHV_g	Low heating value of biogas(MJ/kg)
LHV_w	Low heating value of water(MJ/kg)
R_{eg}	Exhaust gas constant(KJ/Kg k)
Hth	Thermal efficiency (%)

Subscripts

Cw	Cooling water
D	Diesel
Pd	Pilot fuel diesel
G	Biogas
Eg	Exhaust gas
In	Input
W	Water

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I. INTRODUCTION

1.1 Energy:

Energy is defined based on empirical knowledge as a physical quantity as a state of thermodynamics. Energy is ubiquitous in life and we seldom even think about it. In simple words, energy is present in various forms such as electrical, mechanical, chemical magnetic energy etc. In the words of Richard Feynman, "It is important to realize that in physics today, we have no knowledge what energy is. We do not have a picture that energy comes in little blobs of a definite amount." [1]. The distinctive feature of mankind civilization today, one that makes it different from all others is the wide use of mechanical power. At one time the primary source of power for the work of peace or war was chiefly man’s muscle. Later animals are trained to help and later wind and running stream were harnessed. But the greatest revolution took when man learned the energy conversion from one form to another. The machine which does the job of energy conversion is Engine.

1.2 Exergy:

Exergy is defined as the maximum theoretical useful work obtained as a system interacts with an equilibrium state. Exergy is generally not conserved as energy but destroyed in the system.

It is an extensive property of the system and depends on both the state of the system and on the properties of the environment. The state of the environment is referred to as the dead state, defined by the environmental temperature, pressure and composition. In availability analysis of thermal systems, it is customary to divide the availability content of a system into two parts:

(i) The thermo-mechanical availability: It refers to the maximum useful mechanical work extractable as the system comes into thermal and mechanical equilibrium with the surrounding atmosphere. The mass of the system is not permitted to pass or chemically react with the environment. The thermal and mechanical equilibrium are achieved when both the temperature and pressure of the system are equal to that of the environment. This specific state of the system is called the restricted dead state [2].

(ii) The chemical availability: One part of the chemical availability of a system concerns only the system's species that are also present in the environment, known as diffusion availability. Whereas, the other part, called reactive availability, concerns the amount of work developed by allowing species of the system to chemically react with substances of the environment in order to form also environmental species (Chavannavar and Caton 2006). The system achieves the chemical equilibrium when any of its components unable to interact in any way with those of the environment in order to produce work [2].

1.3 Energy and Exergy in Engines:

An Energy-based performance analysis is the performance analysis of a system based on first law of thermodynamics. Even though from 1st law of analysis we are able to find the energy transformations there are further losses at each and every stage and hence only sum part of energy is being available.

An Exergy-based performance analysis is the performance analysis of a system based on the second law of thermodynamics that overcomes the limit of an energy-based analysis. Exergy destruction is a measure of irreversibility that is the source of performance loss. Therefore, an exergy analysis assessing the magnitude of exergy destruction identifies the location, the magnitude and the source of thermodynamic inefficiencies in a thermal system. This provides useful information to improve the overall efficiency and cost effectiveness of a system.

1.4 Engines:

An Engine is a device which converts one form of energy to another form of energy. Normally most of the engines convert thermal to mechanical energy and therefore known as Heat engines. [3]

1.5 Heat Engines:

Heat Engine is a device which transforms chemical energy of fuel to thermal energy and utilizes this thermal energy to perform useful work.

1.5.1 Classification of Heat engines based:

Heat engines are classified into two types based on the combustion chamber. They are:

(1) Internal Combustion Engine:

The Internal combustion Engines is an engine in which the combustion of a fuel (normally a fossil fuel) occurs with an oxidizer (usually air) in a combustion chamber that is an integral part of the working fluid flow circuit. In an internal combustion engine (ICE) the expansion of the high-temperature and high-pressure gases produced by combustion apply direct force to some component of the engine [4].

(2)External Combustion Engine:

An EC engine is a heat engine where an (internal) working fluid is heated by combustion in an external source, through the engine wall or a heat exchanger. The fluid then, by expanding and acting on the mechanism of the engine, produces motion and usable work [5]. Among all the different types of engines Reciprocating IC engine has some advantages over other due to the higher thermal efficiency and weight to power ratio is quite less. The only disadvantage of this is vibration of parts [3].

Further IC engines are further classified into different types based on types of ignition, engine cycle.

1.5.2 Classification of IC engines:

(i) Based on type of Ignition

(a) Spark Ignition (SI) Engine:

An SI engine starts the combustion process in each cycle by use of a spark plug. The spark plug gives a high voltage electrical discharge between two electrodes, which ignites the air fuel mixture in the combustion chamber surrounding the plug. SI engines works on Otto cycle or constant volume heat addition.

(b) Compression Ignition (CI) Engine:

The combustion process in a CI engine starts when the air-fuel mixture self-ignites due to high temperature in the combustion chamber caused by high compression. CI engines are also known as Diesel Engines. CI engines works on constant pressure cycle. CR of CI engines is more when compared to SI engines. Self-ignition temperature of fuels used in CI engines is less when compared to SI engines.

(ii) Based on Engine cycle

(a) Four-stroke cycle**:** A four-stroke cycle has four strokes of piston or two revolutions of crank shaft for each cycle.

(b)Two-stroke cycle: A two-stroke cycle has two strokes of piston or one revolution of crank shaft for each cycle. [3]

(a)Four-stroke cycle: In case of four stroke engines, for both CI and SI engines the ideal sequence of operations is:

(1) Suction stroke
(2) Compression stroke
(3) Expansion stroke
(4) Exhaust stroke

In 4-stroke cycle, there is one power stroke for every two revolutions of crankshaft. There are two nonproductive strokes i.e. suction and exhaust. Therefore if we can make an alternative arrangement for these two strokes without involving the piston movement we can obtain one power stroke for 1 revolution of crank shaft.

(b)Two-stroke cycle:

In case of two-stroke that alternative arrangement can be made by the method of filling the charge and removing the burnt gases from the cylinder. In this, the filling process is accomplished by the charge compressed in the crank case. The induction of the compressed charge moves out the product of combustion through exhaust port. Therefore power stroke is obtained in one rotation of crank shaft.

Overview of 4-stroke and 2-stroke:

In 4-stroke thermal efficiency is more and volumetric efficiency is more due to the more intake timing but power output will be more for a particular size of engine incase of 2 stroke engine. The weight of 2-stroke is less when compared to 4 stroke due to simple mechanism. Therefore if we are concerned about efficiency we opt for 4-stroke and if are concerned about weight low cost compactness we prefer 2-stroke engine [3].

1.6 Types of fuels used in Engines:

Heat Engine is a device which transforms chemical energy of fuel to thermal energy and utilizes this thermal energy to perform useful work. Therefore the characteristics of the fuels play a vital role on the performance characteristics.

Fuels are basically of two types:
(1) Conventional fuels: Conventional fuels include: fossil fuels (petroleum (oil), coal, propane, and natural gas).
(2) Non-conventional fuels: Some well-known alternative fuels include bio-diesel, bio-alcohol (methanol, ethanol and butanol), chemically stored electricity (batteries and fuel cells), hydrogen, non-fossil methane, non-fossil natural gas, vegetable oil, and other biomass sources.
Basically conventional fuels are classified into three types:

(1) Solid fuels
(2) Gaseous fuels
(3) Liquid fuels

To utilize the energy of fuel in most usable form, it is required to transform the fuel from its one state to another, i.e. from solid to liquid or gaseous state, liquid to gaseous state, or from its chemical energy to some other form of energy via single or many stages. In this way, the energy of fuels can be utilized more effectively and efficiently for various purposes.

Solid fuels: Engines using solid fuels like charcoal, powdered coal etc. Generally solid fuels are converted into gaseous fuels before entering into combustion chamber in a separate gas producer.

Solid fuels are mainly classified into two categories, i.e. natural fuels, such as wood, coal, etc. and manufactured fuels, such as charcoal, coke, briquettes, etc. Solid fuels are quite difficult to handle and storage and feeding. Therefore fuels are unsuitable in solid form. [3]

Gaseous fuels: These are the ideal fuels for engines but due to the storage problem and handling problem restrict the use of these fuels in automobiles.

Liquid fuels: Presently Liquid fuels are the fuels which are being used in modern automobiles. Liquid fuels are the derivatives of benzyl, alcohol, petroleum products.

1.7 Important Qualities of Engine Fuels:

Whatever may be the field we search for the optimum utilization of the machine or Engine in an economical and in a safe way. Here we discuss the fuel characteristics for the proper running of SI and CI engines.

1.7.1SI engines:

1) Volatility: The gasoline should be volatile; a certain part of it should vaporize at room temperature to allow easy starting of the engine. Better vaporization of the fuel facilitates its even distribution inside the cylinders, which in turn leads to better acceleration of the vehicle.

2) Dilution of the lubricating oil in crankcase: As the fuel is splashed in the cylinder, some lubricating oil from the crankcase is also washed away with it. This leads to overall decrease in the quantity of the lubricating oil and poor lubrication of the engine's moving parts. To prevent such possibilities, it is important that the type of gasoline used for the engine should vaporize before it gets combusted.

3) Antiknock qualities of the fuel: Abnormal burning or detonation of the fuel inside the engine leads to the effect known as engine knock. During detonation large amounts of heat is released inside the engine which excessively increases the temperature and pressure inside the engine, drastically reducing its thermal efficiency. The fuel should have the tendency to avoid creating the situation of detonation; this quality of the fuel is the antiknock property of the fuel.

The antiknock property of the fuel depends greatly on the self-ignition properties of the fuel, the fuel's chemical composition, and its chemical structure. The fuel most suitable for the SI engines is the one that has highest antiknock property, enabling the engine to work with high compression ratios of fuel, which in turn leads to higher fuel efficiency and higher power production.

4) Gum deposits formed from the fuel: When gasoline is stored for longer periods of time, it has the tendency to oxidize and form gummy, solid substances. When used with an engine, such gasoline will cause sticky valves and piston rings, carbon deposits in the engine, gum deposits in the manifold, clogging of carburetor jets, and enlarging of cylinders and pistons. The gasoline used in the engine should have a tendency to form lower gum content and have a lower tendency to form gum during storage.

5) Low sulfur content: Hydrocarbon fuels may contain sulfur in various forms like hydrogen sulfide and other compounds. Sulfur is corrosive in nature and it can cause fuel line corrosion, carburetor parts, injection pumps, etc. Sulfur also promotes knocking of engine; hence its content in the gasoline fuel should be kept to a minimum [3].

1.7.2 CI engines:

Fuel for CI engines should have certain qualities to be the ideal fuel for these engines. Diesel is used as the fuel in CI engines because it possesses the qualities that are desired from the fuel. Some of the desired characteristics of these fuels are:

1) Knocking characteristics: In case of the CI engine the burning of fuel occurs due to compression of air. It is desired that as soon as the fuel is injected into the cylinder, it starts burning, but in practical situations this never happens as there is always a time lag between the injection of the fuel and burning of the fuel. As the duration of ignition lag increases, more and more amounts of fuel get accumulated in the cylinder head. When the fuel is finally burnt, excessively large amounts of energy is released, which produces extremely high pressure inside the engine. This causes the knocking sound inside the engine, which can be clearly heard. Thus the engines should have a short ignition lag so that the energy is produced uniformly inside the engine and there is no abnormal sound. The ignition of the fuel also affects starting, warming, and production of exhaust gases in the engine.

The knocking capacity of the fuel is measured in terms of cetane rating of the fuel. The fuel you are using for your CI engine should have a cetane number high enough to avoid knocking of engine.

2) Volatility of the fuel: Thorough mixing of the fuel and air when fuel is injected in the cylinder head ensures uniform burning of the fuel. The fuel should be volatile in nature within the operating temperature range of the cylinder head so that it gets converted into a gaseous state and mixes thoroughly with compressed air.

3) Starting characteristics of the fuel: The smooth starting of the vehicle depends greatly on the fuel used for the vehicle. For easy starting of the vehicle it is important that the fuel has good volatility so that it mixes with the air uniformly and it readily forms into the combustible mixture. The high cetane number of the fuel ensures that the ignition of the fuel will be fast, which in turn will lead to faster starting of the vehicle.

4) Smoke produced by the fuel and its odor: The exhaust gases produced from the fuel should not have too much smoke and odor.

5) Viscosity of the fuel: The fuel should have a viscosity low enough so that it can easily flow through the fuel system and the strainer at the lowest working temperatures.

6) Corrosion and wear: The fuel used for the CI engine should not cause corrosion of any components of the engine before or after combustion.

7) Easy to handle: Large quantities of fuel for a CI engine have to be transported from one place to the other. Hence it should be easy to handle and transport. The fuel should have a high flash point and high fire point to avoid it catching fire during transport [3].

1.8 Reason for Alternate fuels:

IC engines are the major consumer of the fossil fuels. In this century, it is believed that Gasoline and diesel will become very scarce and costly. It is also that there will be emissions of greenhouse gases like CO_2 [3]. The stricter emission regulations impel an ‘urgent’ appeal to reduce emissions from diesel engines. Therefore one of the ways to reduce these emissions and scarcity of diesel and gasoline is Alternate fuels. Gaseous fuels receive more prominence in the domain of alternative fuels because of the possibilities of cleaner combustion. The use of new, alternative, and clean-burning fuels as primary energy resources in internal combustion (IC) engines is global interest now-a-days to achieve lower pollutant emissions and higher fuel economy and low content of sulphur. Towards this, the compression ignition (CI) engine of the dual fuel type has been employed to utilize various alternative gaseous fuel resources in place of conventional diesel engines [6].

1.9 Possible Alternatives:

Alternative fuels, known as non-conventional or advanced fuels, are any materials or substances that can be used as fuels, other than conventional fuels. Here we discuss about some of the alternative fuels like CNG, Bio-diesel, alcohol fuels, Biogas, Syn-gas.

(i) Compressed Natural Gas (CNG): CNG consists of mostly methane and is a clean burning alternative fuel. Natural gas can be formulated into CNG or liquefied natural gas (LNG) to fuel vehicles.

(ii) Bio-diesel: Bio-diesel is a form of diesel fuel manufactured from vegetable oils, animal fats, or recycled restaurant greases. Common blends include B2 (2% biodiesel), B5, and B20. B2 and B5 can be used safely in most diesel engines.

(iii) Alcohol fuels: Methanol and Ethanol fuel are primary sources of energy; they are convenient fuels for storing and transporting energy. These alcohols can be used in internal combustion engines as alternative fuels. Butanol has another advantage: it is the only alcohol-based motor fuel that can be transported readily by existing petroleum-product pipeline networks, instead of only by tanker trucks and railroad cars.

(iv) Biogas: Biogas form in anaerobic conditions during the decomposition of organic waste. The composition of biogas, depending on the feed material and the method of digestion, usually lies within the following ranges: 5 0 - 7 0 % methane (CH_4), 2 5 - 5 0 % carbon dioxide (CO_2), 1-5% hydrogen (H_2), 0.3-3% nitrogen (N_2) and various minor impurities, notably hydrogen sulfide (H_2S) [7]. As organic waste is widely available, biogas is a cheap renewable energy to consider.

(v) Syn-gas: Syn-gas is ideally a mixture of two diatomic molecules H_2 and carbon monoxide (CO) produced by gasifying a solid fuel feedstock (such as coal or biomass). Mixtures of H_2 and CO could serve as an alternative spark ignition (SI) fuel due to their high anti-knock behavior.

(vi) Producer gas: Producer gas has a high percentage of N_2 since air is used. Thus it has a low heat value. Producer gas is produced by flowing air and steam through a thick coal or coke bed which ranges in temperature from red hot to low temperature.

However, these fuels are not suitable for compression ignition (CI) concept diesel engine when used alone due to their low cetane numbers and high auto-ignition temperatures. Hence, the CI engine of the 'dual fuel' approach plays a significant role in the efficient utilization of a wide range of gaseous fuels.

1.10 Biogas in SI engines and CI engines:

The interest on an effective utilization of renewable energy Sources to produce electrical energy has been increasing due to not only energy security perspective but also environmental concerns raised by use of fossil fuels. Biogas is one of the representatives of such energy sources and can be obtained from biomass or biodegradable organic wastes in an anaerobic digester [8].

As a fuel, biogas has an extremely low energy density on the volume basis an account of its high CO_2 content. The flame speed is just 25 cm/s [9]. The large quantity of CO_2 present in biogas lowers its calorific value, flame velocity and flammability range compared with natural gas. The self-ignition temperature of biogas is high and hence it resists knocking which is desirable in SI engines. Thus biogas has a high anti-knock index and hence biogas engine can use high compression ratios, which can lead to improvements in thermal efficiency [10].Another approach for better engine performance is a biogas diesel dual fuel engine[11,12,13] . In this case, mixture of gaseous fuels and fresh air is supplied to a cylinder and then, a small amount of diesel-like fuel is injected to ignite the combustible mixture. Since it is usually converted from a diesel CI engine, the dual fuel engine has a high compression ratio. This means that it can achieve higher efficiency than a biogas dedicated SI engine [8].

Selection of choice of engine depends on the following points
(1) If the gas amount is assured we can use SI engines and there will be a development of 85% rated power [14].
(2) If the gas is not assured we can use CI engines and there will be a 100% development of rated power [14].

Table 1.1 Chemical Composition of Biogas

Components	Household waste	Wastewater treatment plants sludge	Agricultural wastes	Waste of Agrifood industry
CH_4 (% vol)	50-60	60-75	60-75	68
CO_2 (% vol)	38-34	33-19	33-19	26
N_2 (% vol)	5-0	1-0	1-0	-
O_2 (% vol)	1-0	< 0.5	< 0.5	-
H_2O (% vol) at 40° C	6	6	6	6
Total (% vol)	100	100	100	100
H_2S (mg/m^3)	100 – 900	1000 – 4000	3000 – 10000	400
NH_3 (mg/m^3)	-	-	50 – 100	-
Aromatic (mg/m^3)	0 – 200	-	-	-
Organochlorinated (mg/m^3)	100-800	-	-	

1.11 Properties of Biogas:

1) Biogas has high octane no
2) Good anti knocking properties
3) Easily available
4) Octane no. with CO_2=110 (without CO_2 =130)
5) Ignition Temperature =651 ^{0} C

1.12 Dual Fuel technology:

Biogas cannot be used to run a CI engine directly on account of its high self-ignition temperature. However, it can be utilized in a CI engine with the dual fuel-ling approach. The dual fuel engine is basically a modified CI engine. DFT primarily consists of two fuels. One is primary fuel which is gaseous fuel on which the engine runs primarily and the other fuel is pilot fuel which is used for initiation of ignition. In this case, a mixture of air and biogas or other gaseous fuel is sucked into the engine, compressed and then ignited by a spray of fuel with a low self-ignition temperature like diesel, vegetable oil or bio-diesel, which is called a pilot fuel. Dual fuel operation always needs a small amount of pilot fuel for ignition.

Here, the important point is the ignition starts as in the case of CI engines the flame front propagates in the fashion of SI engines.

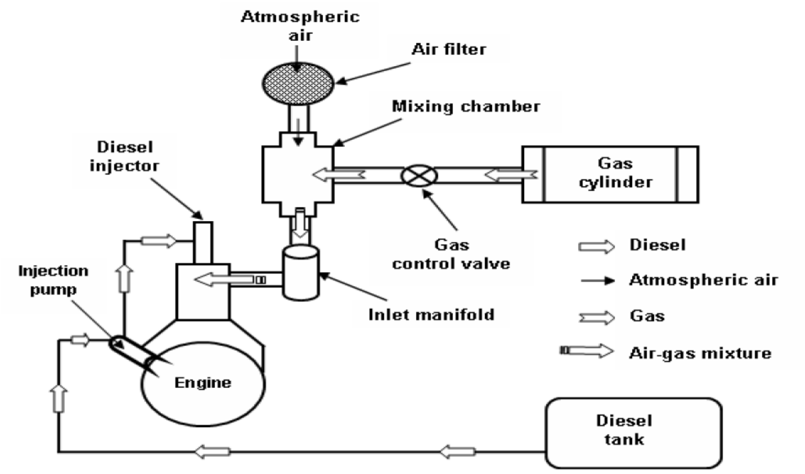

Figure 1.1 Schematic Diagram of Dual Fuel Diesel Engine

Factors effecting combustion in Dual Fuel Engine:

1) Cetane no. of pilot fuel.

2) Amount of pilot fuel.

3) Injection Timing.

4) Compression Ratio.

5) Nature of gaseous fuel.

Chapter 2
EXPERIMENTAL SETUP AND PROCEDURES

2.1 Experimental set up

The experiments are carried out in a VCR engine. The VCR set up is modified into a Dual- fuel set up by connecting a gas mixer in the inlet manifold .

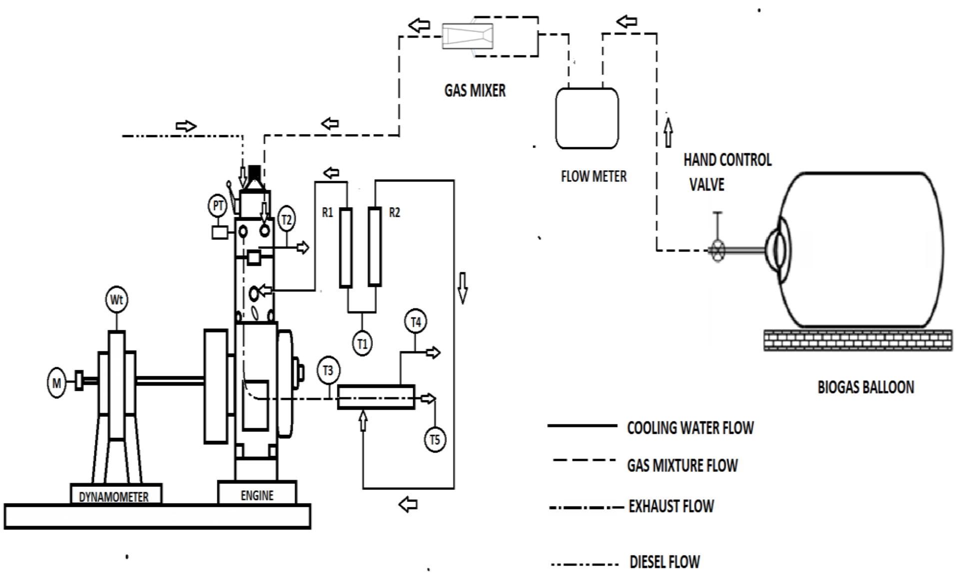

Figure 2.1 shows the experimental set-up

Fig. 2.1 represents the experimental set-up. The setup consists of single cylinder, four stroke, VCR (Variable Compression Ratio) Research engine connected to eddy current dynamometer. It is provided with necessary instruments for combustion pressure, crank-angle, airflow, fuel flow, temperatures and load measurements. These signals are interfaced to computer through high speed data acquisition device. The set-up has stand-alone panel box consisting of air box, twin fuel tank, manometer, fuel measuring unit, transmitters for air and fuel flow measurements, process indicator and piezo powering unit. Rotameters are provided for cooling water and calorimeter water flow measurement. In petrol mode engine works with programmable Open ECU, Throttle position sensor (TPS), fuel pump, ignition coil, fuel spray nozzle, trigger sensor etc. The setup enables study of VCR engine performance for both Diesel and Petrol mode and study of ECU programming. Engine performance study includes brake power, indicated power, frictional power, BMEP, IMEP, brake thermal efficiency, indicated thermal efficiency, Mechanical efficiency, volumetric efficiency, specific fuel consumption, Air fuel ratio, heat balance and combustion analysis. Lab view based Engine Performance Analysis software package "Enginesoft" is provided for on line performance evaluation. A computerized Diesel injection pressure measurement is optionally provided.

Table 2.1 shows the specification of the engine

Parameters	Specifications
Engine type	DI
General details	Single Cylinder, water cooled
Stroke	4-sroke
Cylinder diameter	87.5mm
Connecting rod length	234mm
Orifice diameter	20mm
Compression ratio	17.5
Rated output	3.5kw at 1500rpm
Dynamometer arm length	185mm
Fuel Injection opening	23 degrees BTDC

.

2.2 Measurements:

(1) A piezoelectric pressure transducer is mounted flush with the cylinder head surface to measure the cylinder pressure. These signals are interfaced with computer through engine indicator for pressure-crank angle ($P - \theta$), pressure-volume (P - V) plots and engine indicated power.

(2) The air flow to the engine is monitored by passing the intake air through an air box with orifice meter and a U tube manometer. The engine loading is done by an eddy current dynamometer.

(3) The specific heat of the exhaust gases can be determined by installing a calorimeter of counter flow pipe-in pipe heat exchanger.

(4) Six thermocouples (K-type) are fitted at relevant positions for the measurement of temperatures at the required positions.

(5) Flue gas analyzer for the measurement of emissions like CO_2, NO_2, NO_x, CH_4etc

(6) Rota-meter for the measurement of flow of water to engine and calorimeter.

The gas installation circuits assisting with various measuring instruments are added to the base diesel engine for the dual fuel operations. The necessary equipments are designed, fabricated and also modified.

2.3 Experimental Procedures:

First, engine was warmed up and run for few minutes at 1500 rpm under no-load condition to reach stable operating conditions. The water flow was adjusted to 300 and 100 liters per hour for the engine cooling and calorimeter respectively. Then, as per experimental design a load level was set for engine operation. Once the engine reaches the steady-state condition, the engine was ready to present the baseline results.

For this, the following data were recorded manually:

1) Engine jacket water (in/out), calorimeter water (in/out) and exhaust gas temperature,

2) The difference in liquid level in the manometer for air flow, and

3) Volume of diesel fuel consumption by the engine in one minute.

After setting the above inputs manually to the computer software program, the data were converted to engineering units and were updated and displayed on a monitor at every second. The crank angle measurement was sensed by an optical sensor and then was acquired on a PC at time interval of two-degree CA. The engine peak cylinder pressure and $P - \theta$ diagram were recorded for each tested load. The load was varied in steps by means of the eddy-current dynamometer with the help of a manually controlled knob with a digital load indicator provided in the engine controller. This experimental measurement procedure was repeated for 0%, 20%, 40%, 60%, 80% and 100% engine loading. The load variations on the engine were conducted at 1500 ± 50 rpm.

For the biogas dual fuel operation, biogas flow was opened up slowly from gas balloon and allowed biogas to reach gas carburetor. The homogeneous air-gas mixture from carburetor was then sucked into the cylinder to take part in the dual fuel combustion via engine manifold. The amount of biogas was increased manually till engine shows signs of misfire. This limits the maximum biogas flow for the dual fuel operation. During the process, engine speed increased due to added extra chemical energy from biogas. To maintain a constant level power and speed from both diesel and dual fuel modes, the quantity of diesel was varied by adjusting liquid fuel cut-off valve. Finally, the cut-off valve was locked manually at the rated engine speed of 1500 rpm. This means that the engine operated with minimum pilot consumption at these operating conditions. Now, at a steady-state dual fuel operation, again the same input manual parameters, as described for baseline tests, were inserted into the computer software program for efficiency and combustion results.

Chapter 3
EXPERIMENTAL OBSERVATIONS

Table 3.1 Energy analysis of diesel and biogas dual mode of operations at various loads

Load (%)	Fuel type	Q_{in}		W_{shaft}		$Q_{cooling}$		$Q_{exhaust}$		$Q_{uncounted}$	
		kW	%	kW	%	kW	%	kW	%	kW	%
0	Diesel	5.32	100	0.09	1.71	2.33	43.77	1.32	24.86	1.57	29.64
	Dual	9.31	100	0.10	1.082	2.50	26.86	1.65	17.72	5.06	54.32
20	Diesel	6.49	100	0.71	11.03	2.44	37.61	1.42	22.01	1.90	29.33
	Dual	9.02	100	0.55	6.14	2.65	29.41	1.88	20.85	3.93	43.58
40	Diesel	7.85	100	1.45	18.46	2.74	34.96	1.705	21.71	1.95	24.85
	Dual	11.33	100	1.50	13.27	2.92	25.78	2.17	19.16	4.73	41.77
60	Diesel	9.22	100	2.11	22.90	2.99	32.47	2.045	22.18	2.06	22.43
	Dual	11.73	100	2.01	17.18	3.006	25.61	2.84	24.24	3.86	32.96
80	Diesel	10.56	100	2.75	26.11	3.26	30.89	2.50	23.67	2.04	19.31
	Dual	12.49	100	2.73	21.87	3.22	25.84	2.96	23.72	3.56	28.55
100	Diesel	12.03	100	3.44	28.63	3.56	29.60	2.98	24.80	2.04	16.961
	Dual	13.66	100	3.29	24.10	3.56	26.11	3.004	21.98	3.797	27.79

Table 3.2 Exergy analysis of diesel and biogas dual mode of operations at various loads

Load (%)	Fuel type	A_{in}		A_{shaft}		$A_{cooling}$		$A_{exhaust}$		$A_{destroyed}$		Exergy Efficiency
		kW	%	kW	%	kW	kW	kW	%	kW	%	%
0	Diesel	5.50	100	0.09	1.66	0.06	1.09	0.35	6.48	5.0007	90.75	9.24
	Dual	9.19	100	0.100	1.09	0.070	0.769	0.10	1.12	8.91	97.00	2.99
20	Diesel	6.71	100	0.71	10.67	0.06484	0.966	0.40	6.01	5.52	82.34	17.65
	Dual	8.84	100	0.55	6.27	0.077	0.877	0.17	1.92	8.04	90.92	9.076
40	Diesel	8.12	100	1.45	17.86	0.07	0.95	0.49	6.09	6.09	75.08	24.91
	Dual	11.09	100	1.50	13.56	0.089	0.808	0.35	3.23	9.14	82.39	17.60
60	Diesel	9.53	100	2.11	22.15	0.08	0.92	0.61	6.42	6.719	70.49	29.50
	Dual	11.46	100	2.01	17.58	0.094	0.825	0.52	4.61	8.82	76.97	23.02
80	Diesel	10.91	100	2.75	25.26	0.10	0.91	0.7	7.09	7.28	66.72	33.27
	Dual	12.20	100	2.73	22.38	0.105	0.865	0.66	5.41	8.70	71.33	28.66
100	Diesel	12.43	100	3.44	27.69	0.115	0.92	0.98	7.95	7.88	63.42	36.57
	Dual	13.19	100	3.29	24.96	0.123	0.93	0.82	6.23	8.95	67.86	32.13

Chapter 4
THERMODYNAMIC ANALYSIS

Energy is a fundamental concept of thermodynamics and one of the most significant aspects of engineering analysis [17].It is crucial to know the maximum possible performance of the dual fuel modes which can provide a vital comparison parameter with base engine. In addition, impact of process changes such as, load and pilot fuel quality etc. in the system in terms of system losses is also to be assessed. These findings will help in reducing the available energy loss to improve the overall engine performance.

Towards this, this chapter discusses both the energy and exergy balance of the diesel and dual fuel operations. Initially, the first law analysis is presented for both the diesel and dual fuel modes. This analysis is shown in order to assist the comprehension of the second law analysis to follow.

4.1 First law analysis

The energy input (Q_{in}) in any IC engine is contained in its fuel.

This amount of input energy is then converted into other forms. In an engine, the input chemical energy of fuel is usually converted to the following forms

1) Useful work output or shaft energy ($P_{shaft);}$
2) Energy transferred to cooling water (Q_{cw});
3) Energy transferred to the exhaust gases (Q_{eg}); and,
4) Uncounted losses ($Q_{uncounted}$) due to friction, radiation, heat transfer to surroundings, operating auxiliary equipment, etc.

The amount of each of these energies stated above evaluated on the basis of the first law of thermodynamics is now described.

1) The input energy (Q_{in}) to the diesel engine is the amount of fuel energy content in the supplied fuel and it is given by,

For a diesel mode,

$Q_{in} = [(M'_d /3600)*LHV_d]$ kW

For a dual fuel mode,

$Q_{in} = \{[(M'_{pd}/3600)* LHV_{pd}] + [(M'_g/3600)*LHVg]\}$ Kw

2) The energy converted to shaft output,

$P_{shaft} = 2* \Pi * N * W * r$; kW

3) The heat loss from the engine block to the cooling water is given by,

$Q_{cw} = [M'_{we}* Cp_w* (T2-T1))]$; kW

4) The energy wasted in form of exhaust gas losses is evaluated by,

$Q_{eg} = [M'_{eg} * Cp_{eg} * (T5-To)]$; kW

Where, the physical property of the exhaust gas (the value of Cpeg) can be determined from the energy balance of flows passing through the calorimeter as follows:

$Cp_{eg} = [M'_{wc} * Cp_w * (T4-T3)] / [M'_{eg} *(T5- T6)]$ Kj/Kg k and

$M'_{eg} = M'_a +M'_d$ (for diesel)

$M'_{eg} = [M'_a+ M'_{pd} + M'_g]$ (for dual fuel)

5) The amount of the uncounted losses is determined by performing an energy balance and is given by,

$Q_{uncounted} = [Q_{in} - (P_{shaft}+ Q_{cw} + Q_{eg})]$ kW

4.2 Exergy analysis:

The knowledge of 'how the energy is lost' will help in finding means to reduce the same to improve the performance of the engine in terms of efficiency and power output [2]

The second law analysis indicates various forms of energy that have different levels of ability to do useful mechanical work. This ability to perform useful mechanical work is defined as availability. In an IC engine, the availability input (A_{in}) which contained in its chemical availability of fuel is converted into other exergy forms.

In an engine, the input fuel availability is converted into the following forms:
i. Useful work output or shaft availability (A_{shaft});
ii. Availability transferred to cooling water (A_{cw});
iii. Availability transferred to the exhaust gases (A_{eg});
iv. Uncounted availability destructions ($A_{destoyed}$) due to friction, radiation, heat transfer to surroundings etc.

From the second law of analysis, now we calculate all the availabilities transferred.

1) Chemical availability of fuel or input availability,
For diesel mode
A_{in}= [1.0338 * M'_d* LHV_d] kW
For Dual fuel mode,
A_{in}= [A_{pd}+A_g] Kw;
Where A_{pd}= (1.0338 *M'_{pd}* LHV_{pd}) Kw and A_g = (.95 * M'_g* LHV_g) kW;

2) Shaft availability
A_{shaft} = Brake power output (kW);

3) Availability transferred to cooling water (A_{cw}):
A_{cw} = {Q_{cw} - [(M'_{we} /3600) *Cp_w* T_o * ln (T2/T1)]} kW;
4) Availability transferred to the exhaust gases:
A_{eg}= {Q_{eg} + [M'_{eg}/3600 * T_o *(Cp_{eg} * ln (T_o/T_5) –R_{eg}ln (P_o/P_{ego}))]} kW;
5) Destroyed availability:
$A_{destroyed}$= [A_{in}– (A_{shaft}+ A_{shaft}+ A_{eg})] kW;
The exergy efficiency (η_{II}) is the ratio of total availability recovered from the system to the total availability input into the system. The recovered availability includes A_{shaft}, A_{eg} and A_{cw}.
Therefore,
η_{II}= (Availability recovered/Availability input)
η_{II}= 1 – ($A_{destroyed}$ /A_{in})

Chapter 5
RESULTS AND DISCUSSION

From the dual fuel mode viewpoint, it is very essential to have the knowledge of available fuel energy losses or destroys whereabouts in the engine operations [2]. Therefore in this chapter, the first and second law are coupled together in order to get a clear view of the dual fuel operation of Biogas.

Therefore, in this chapter the effect of load and pilot fuel variation in the energy and exergy balances of the dual fuel operations are evaluated and compared to that of the baseline diesel mode.

The various calculated energies and exergies are illustrated in Table 3.1 and 3.2.

5.1 Performance parameters

At an individual tested engine loads, both shaft power and torque outputs were kept equal in magnitude for both diesel (baseline) and dual fuel operation. From Fig. 5.1, it can be seen that the brake power and torque increased gradually with an increase in load. It is obvious because, at constant engine speed, as load increases both torque and power output increase.

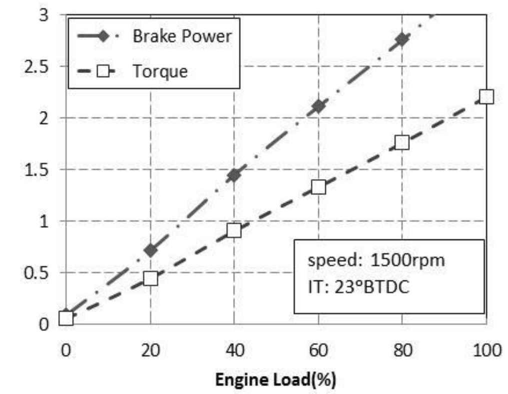

Figure 5.1 variation of shaft power and torque with load

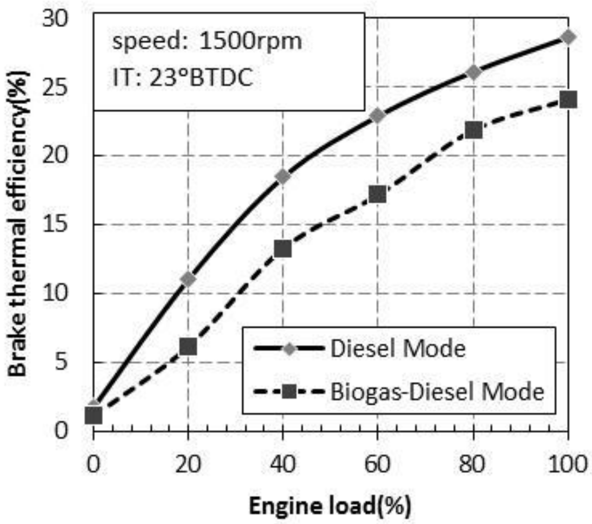

Figure 5.2 Variation of brake thermal efficiency with load

Fig 5.2 shows a comparison of the brake thermal efficiency and engine load for combustion modes and test fuels at engine speeds of 1500 rpm. To evaluate the effect of engine load and induced biogas on the rate of thermal efficiency, the engine loads were varied from 20% to 100% increments of 20% load. It can be seen from figure that the thermal efficiency of dual-fuel combustion for pilot fuels was at lower levels than those of the single-fuel mode at all ranges of engine loads. The lower thermal efficiency of the dual-fuel mode was generally due to the effect of biogas residuals, combusted residual gas, low combustion temperatures, and higher total fuel flow rate during the combustion process. It was also due to the reduction in thermal efficiency resulting from the decreased flame propagation speed [18].

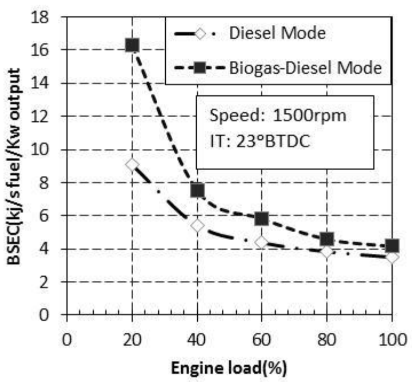

Figure 5.3 Variation of brake specific energy consumption with load

Brake specific energy consumption (BSEC) of a dual fuel mode was calculated from the data of fuel consumption rate and LHV of pilot liquid fuel (diesel) and biogas. The BSEC of the engine was higher at part loads (up to 40%) used shown in Fig. 5.3. This is due to the poor combustion efficiency of biogas fuelled dual fuel modes [2].The presence of carbon dioxide in the biogas cut down the burning velocity and thereby resulted in incomplete combustion that increased the BSECs of both the dual fuel modes.

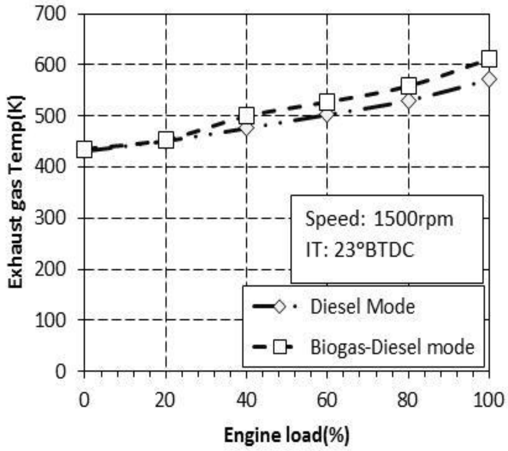

Figure 5.4 Variation of exhaust gas temperature with load

In the process, both the dual fuel modes established higher exhaust gas temperatures (about 400^0 C to 700^0 C) than that of diesel mode (Fig5.4). In diesel since the ignition takes place near to TDC there will be a good transfer of heat to work and less amount of heat is lost through exhaust whereas in Dual mode there will be a ignition delay and hence more exhaust temperature [19].

5.2 Availability Analysis:

The experimental investigations of dual fuel operation reveal reductions in thermal efficiencies as compared to diesel mode. The different exergy variations and exergy efficiency of Diesel and dual fuel mode are represented separately in fig. 5.5 and fig. 5.6 respectively.Figure 6.7 shows the percentage of fuel availability exchanged through destroyed availabilities (irreversibilities) versus load for the tested fuel modes. The availability destruction decreased with the increase of load. This is because of the increase in combustion temperatures, decrease in combustion duration, and decrease in entropy generation during oxidation. Due to presence of a significant part of chemically inert CO_2 in biogas, the combustion temperature of dual fuel modes reduced. This caused a reduction in both the fuel availability and work output of the dual fuel modes. It affects the decrease of second law efficiency and an increase in the percentage of fuel availability destroyed in the form of irreversibility [2].

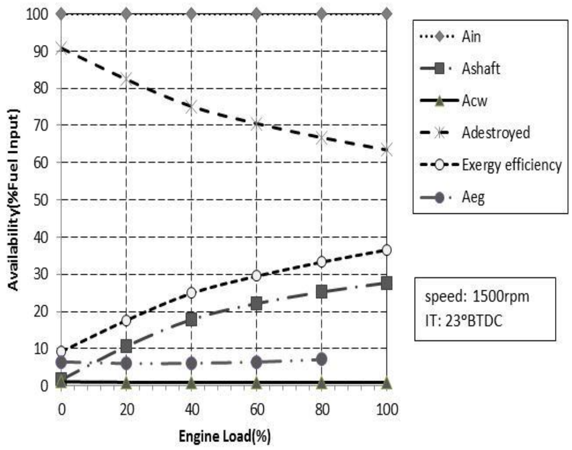

Figure 5.5 Availability distribution with fuel input as function of load(Diesel mode)

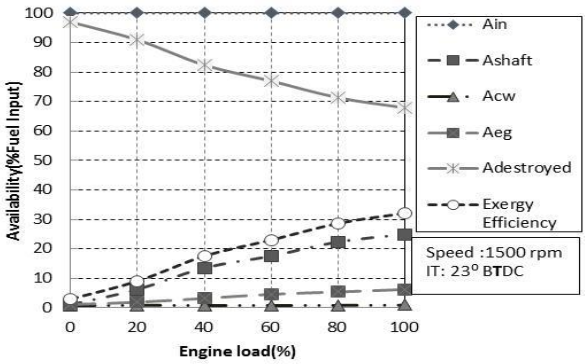

Figure 5.6 Availability distribution with fuel input as function of load(Biogas-Diesel mode)

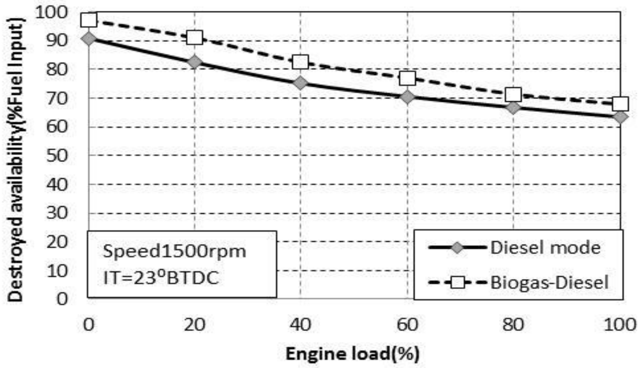

Figure 5.7 Destroyed availability distribution at different engine load

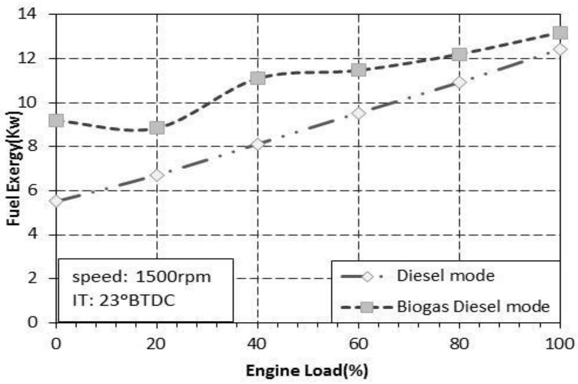

Figure 5.8 Chemical Fuel Exergy versus load

Fig 5.8 represents the graph between Fuel exergy Versus Engine load of the diesel and dual fuel mode operation. To maintain an equal power output as of diesel mode, dual fuel mode required higher chemical fuel exergy than the diesel mode due to the poor combustion and low energetic biogas fuel [2]. Therefore the figure shows that A_{in} of dual flow is more than only diesel flow. At lower loads, the lean air mixture decreases the fuel availability.When load was increased, to produce higher shaft output at respective loads, the enhanced rate of fuel energy increased the amount of kW available fuel input. In the process, a higher kW shaft availability was resulted at higher engine loads.

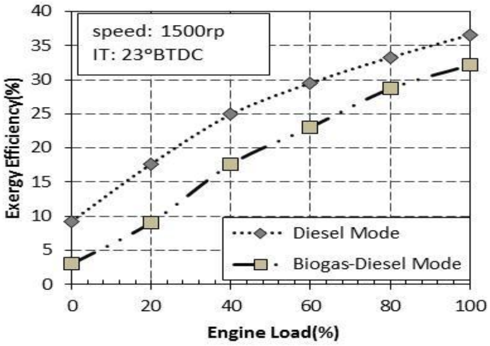

Figure 5.9 Exergy efficiency versus Load

From the Fig. 5.9,it is clear that as the load increases the exergy efficiency increase. This is due to as load increases during engine operation; the rich fuel mixture increased the combustion temperature. Therefore, increased work availability and reduced heat transfer availability losses were obtained, as percentages of the fuel chemical availability. For this, an increase in the exergy efficiency resulted at higher loads for all the tested fuels [2]. In case of Biogas at higher loads the exergy efficiency improves significantly than compared to lower loads due to the improved combustion of Biogas at higher load and decreased ignition delay [2]. Because of the improved combustion of biogas at higher loads, the exhaust gas availability was increased. In addition, the shaft availability of the fuels was higher for an increased load.

Chapter 6
CONCLUSIONS

Diesel engines are established as a unique combination of energy efficiency, power, reliability, and durability. They play a vital role in transport sectors, farm and construction purpose, power generation, etc. Because these engines adopt fossil diesel fuel-based technology, they contribute to greenhouse gases by producing CO and CO_2 emissions. In order to reduce these carbon emissions, there are possible and available clean diesel technologies viz., alternative fuels, hybrid-electric power and fuel cell etc. Use of clean gaseous fuel, alternative to diesel, is one of the techniques which have the potential for reducing greenhouse gas emissions. Comprehensive literature review suggests that the engine operating and design parameters namely load, speed, compression ratio, pilot fuel injection timing, pilot fuel mass, intake manifold conditions, and type of gaseous fuel, have effects on the performance, combustion, and emission characteristics of dual fuel diesel engines. As a first step, optimization of engine parameters such as, load, pilot quality and gaseous fuel type are performed in this study. In this connection, a gas circuit to be added with the base diesel setup for dual fuel operations is developed and the necessary equipments are fabricated. The diesel engine is then run with 100% standard diesel as baseline tests for reference results. This diesel mode is operated for the entire load range (0 to 100% in steps of 20%), and the outcome of efficiency, combustion and emission characteristics are analyzed and discussed elaborately. At equal power output condition, the dual fuel engine performance is compared to that of baseline case. Additionally, to explore the exergy losses whereabouts, the entire experimental results are analyzed thermodynamically and compared.

The conclusions we obtained from this experiment are:

(1) The presence of CO_2 in the biogas reduced the burning velocity, and thereby, resulted incomplete combustion that increased the BSEC and exhaust gas temperature of dual fuel modes. Including this, the longer pilot ignition delay and high self-ignition temperature of biogas helped delaying the dual fuel combustion process more into the expansion stroke. All these factors lowered the thermal efficiency.

(2) The increase in load resulted an increase in exergy efficiency for all the tested fuel mode conditions. For the dual fuel operations, beyond 20% load, exergy efficiency was increased significantly due to improved combustion of biogas at high temperature zones. However, due to presence of about 41% CO_2 volume in biogas, the cumulative work output of the dual fuel modes have been lower, and hence, this resulted lower exergy efficiency for dual fuel mode.

(3) It is noticed that dual fuel mode require higher fuel exergy (due to their poor combustion of fuel-air mixture and lower fuel energy content) for producing same amount of shaft output compared to its diesel mode.

(4) Even though destroyed availability decreases as the load increases due to the presence of CO_2 in biogas it is more compared to Diesel mode.

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