Chapter-2

Experimental Investigations of the Producer Gas for Tar Removal

In this chapter, we discuss the effect of producer gas when used together with diesel as a fuel to run the dual-fuelled diesel engine. Producer gas is obtained when the solid biomass feedstock (wood and coconut shell used alone one by one and then mixed with Calcium oxide (CaO) 10% by weight) is used as fuel to run downdraft gasifier system. In addition, suitable tar removal approach used for cleaning producer gas. In section §2.1, we present a brief introduction. In §2.2, we present the design parameter of the downdraft gasifier system. We then present the operating parameters of the downdraft gasifier system in §2.3. In §2.4, we discuss the working principle of the downdraft gasifier system followed by technical specification, instruments used, experimental procedure, observations and analysis. We then discuss on needs for cleaning the producer gas in §2.5, followed by types of tar §2.5.1, under tar removal approach, classification of catalyst, methodology, observation and analysis while conducting experiments. In section §2.6, uncertainty analysis has been presented. We then present the concluding remarks in §2.7.

2.1 Introduction

The utilisation of waste biomass as a feedstock for gasification system to produce producer gas is the best option. This producer gas is used as a fuel to run the diesel-fuelled engines alone or with the diesel to fulfilling the shortage of existing fuel. A solid feedstock is used as a fuel for the gasifier system to obtain the producer gas. The size of the feedstock decides the type of gasifier system to be used. Producer gas is the combination of gases like- CO, CO_2, H_2, CH_4, N_2, NO, etc., tar and dust particles. For getting the best results when producer gas is used as fuel the impurities like- tar and dust particles need to be cleaned. These impurities create severe problems such as choking, scratching, blocking etc. which affect the efficiency of the plant/engine got reduced. In this chapter, we adopt the primary tar filtration method for cleaning the producer gas.

2.2 Designed parameters

Following parameters needs to be considered for designing the gasifier system. According to the feedstock availability downdraft gasifier system is preferred for the experiments because it removes more amount of tar, better efficiency (70 – 85%), low cost and suitable for wood, coconut shell and other type of solid feedstock which are having size 2.5 *cm* × 2.5 *cm* for gasification.

2.2.1 Reactor height:

The reactor height from top to bottom can be finding by the use of this expression. The parameter depends on *SGR*, operating time and density of the fuel [1].

$$\frac{\mathrm{SGR} \times \mathrm{t}}{\rho_{\mathrm{r}}} \tag{2.1}$$

where, *SGR* stands for specific gasification rate $(kg/hr \times m^2)$, t stands for operating time *(min)*, ρ_r means density of the fuel (kg/m^3).

2.2.2 Reactor diameter:

Given expression is used to determine the reactor diameter [2].

$$\sqrt{\frac{1.27\times \mathrm{FCR}}{\mathrm{SGR}}} \tag{2.2}$$

where, *FCR* stands for Fuel consumption rate *(kg/hr)*, *SGR* stands for specific gasification rate $(kg/hr \times m^2)$.

2.2.3 Throat design:

Gasifier throat is nothing but the reduction of area just before the oxidation zone which provide the uniform motion to devolatilized or pyrolyzed biomass and allowing uniform distribution of temperature and sufficient time for tar cracking into small molecules of hydrocarbon. Throat dimensioning is related to the “Hearth load” concept.

2.2.4 Hearth load (B_g):

Hearth load is the ratio of amount of fuel consumed to the surface area of the throat (B_S), expressed as $Kg\text{-}m^3/cm^2\text{-}h$. It is given that for one kilogram of dry fuel under normal conditions produces about 2.5 m^3 of producer gas. The relation between B_g and B_s is given by: $B_g = 2.5\ B_S$. Hearth load depends on the temperature and heat insulation of hot zone. A maximum value of 0.9 indicates that the gasifier is in good operation. Higher value of hearth load increases the pressure drop over the reduction zone of the gasifier. The gasifier produces less tar or tar free when it should be properly insulated and maintained the hearth load value between 0.15 and 0.18 [3].

$$\text{Max. } B_g = \frac{\text{Gross Volume}}{\text{Surface area of the throat}} \tag{2.3}$$

Throat diameter can be determined by the use of above expression. Also, standard calculation for reactor dimensions is available in [4].

2.3 Operating parameters of gasifier system

2.3.1 Residence time and heating rate:

Residence time and heating rate go hand in hand in every zone. These parameters affect the tar levels, phase transformations of the biomass fuel. Different products are obtained for different values of these parameters. A pre-heated feedstock, heating rate gets faster and residence time is brought down to lesser time period for yielding the same product. Carlos [5] explains the effects of pre-heating feedstock with various pellet sizes on heating rate and resulting constituents of the product gas.

2.3.2 Air flow rate:

Air is a gasifying agent used in combustion zone to partially oxidize the devolatilized biomass. The parameter is useful to determine the fan size or blower which is need to fixed along the sides of the reactor. Parameter depends on equivalence ratio, fuel consumption rate, stoichiometric rate of fuel and density of air. Air flow rate can be calculated by following expression.

$$\frac{\epsilon \times \mathrm{FCR} \times \mathrm{SR}}{\rho_a} \tag{2.4}$$

where (ε) stands for equivalence ratio, *FCR* means fuel consumption rate *(kg/hr), SR* means stoichiometric rate, ρ_a stands for density of air *(kg/m^3)*.

2.3.3 Operating temperature:

Amount of oxygen feed to the gasifier system depends on the operating temperature. Oxidation reactions are exothermic reactions which release heat energy that become the source of whole gasifier system to work properly and to process pyrolysis and combustion zone also. Once the gasifier temperature reaches the self-ignition temperature of the biomass then the gasification process becomes self-sustaining and solely depends on the oxygen source [6].

2.3.4 Equivalence ratio:

Equivalence ratio *(ER)* is the ratio of actual air-fuel ratio to stoichiometric air- fuel ratio. The parameter refers when air and oxygen is used as a gasifying agent. It helps to determine the tar concentration present during gasification. By increasing the *ER* tar formation in the product gas can be reduced. High *ER* means greater oxygen content allowed to react with the volatiles present in the combustion zone. When air is used as a gasifying agent for the gasification process, the suitable value for *ER* is between 0.25 to 0.3. Variation in the *ER* affects the energy in the product gas, gas composition, gasification temperature and conversion of energy from char to gas. For complete oxidation of biomass with air a weight ratio (mass of air/ mass of biomass) of 6.36 is required whereas with oxygen a weight ratio of 1.476 is needed. So, to convert all char into gas as Equivalence ratio 0.25 has been more preferred.

The conversion rate of part of wood energy to gas reaches maximum. Air filtered from nitrogen, dust particles and other impurities enters the reactor with more oxygen content. Using such a filtered air is recommendable to improve the efficiency of the gasification and quality of the product-gas.

2.4 Working principle

Figure 2.1 shows the photograph of downdraft gasifier system.

Figure 2.1: Downdraft gasifier system, an experimental setup for obtaining producer gas using solid biomass feedstock as a fuel. It is installed at IIT (BHU).

The main parts of the gasifier system have also been indicated in the figure 2.1. Due to possibility of vibration during running, the system was fixed on a concrete platform as shown in figure 2.1. Firstly, wood reaches the reactor chamber through the hopper which is placed at the top. In the reactor the firing of wood takes place which starts after initial burning for one hour. Initially the wood supplied is dried which is followed by pyrolysis.

Thermo chemical decomposition of organic material at elevated or high temperature in absence of oxygen is called Pyrolysis. After pyrolysis the next process which takes place inside the reaction chamber is combustion followed by reduction of the products which finally gives rise to producer gas which contains significant amount of tar, particulate matter, and other impurities. After the producer gas comes out of reaction chamber it then passes through the pack column where the gas is showered by water to remove initial amount of tar and other impurities but due to high temperature of gas, water turns into steam and passes along with the gas.

Table 2.1: Parts name of gasifier system.

Part No.	Parts name	Part No.	Parts name
1	Hopper (Feedstock in)	9	Venturi
2	Reactor first	10	Water collecting tub
3	Air nozzle	11	Blower
4	Down draft	12	Cyclone separator
5	Reactor second	13	Gas testing point
6	Water seal	14	Three- way filter
7	Primary gas outlet through pack column	15	Primary gas out from gasifier unit
8	Water shower		

This mixture is then passed into a venturi, which placed adjacent to pack column, in which the separation of steam from the mixture and condenses down.

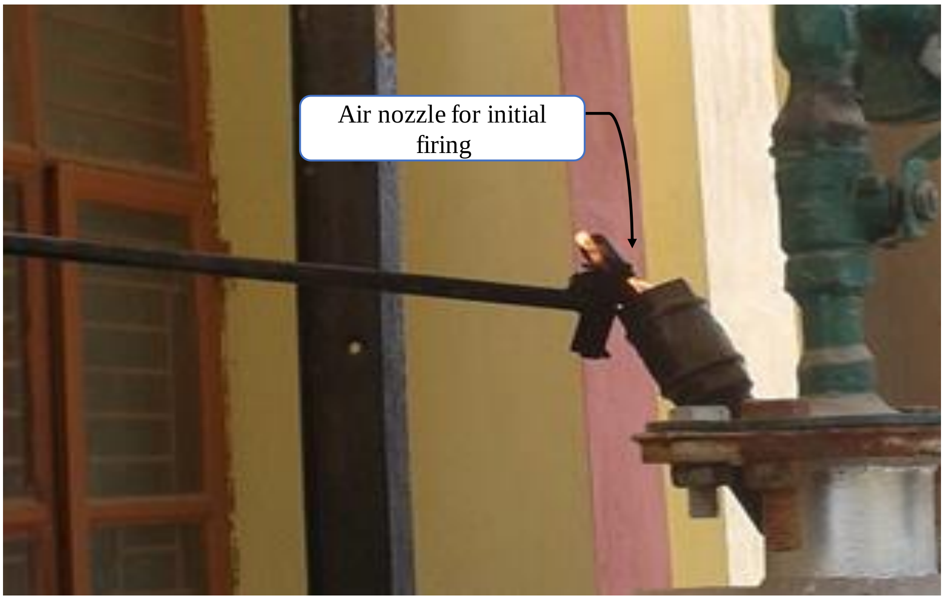


Figure 2.2: Air nozzle of downdraft gasifier system.

Figure 2.3: Quality gas test at chimney. The producer gas flame colour is an indication of its quality. At the beginning of the operation, the producer gas flame colour was misty red this is due to the presence of unburned gases, but later on, the flame colour turned uniformly dense red colour at the steady-state condition.

The blower sucks the gas from the drain box and pushes it into the cyclone separator. In the cyclone separator the particulate matters are settled down. Even if some of the impurities are left in the producer gas, they are eliminated through the use of catch pot. After this the producer is passed through the chimney for a quality test of producer gas. If the producer gas catches fire then the valve is closed and the gas is allowed to pass-through three-way gas filter. The three-way gas filter is a filter which has three chambers in which the first is filled with rice husk, second one is filled with woody waste and the third chamber is filled with cotton. If the moisture is still remaining in the producer gas, it can be removed by the moisture drain valve. Now the producer gas is only free from those tar which is soluble in the water but still polluted by rest tar which is not soluble in the water and still remain in the producer gas as well as other impurities hence the mixture of existing impurities with the producer gas is known as primary gas.

2.4.1 Technical specification:

Following are the technical specification of existing experimental setup downdraft gasifier system.

Table 2.2: Technical specifications and salient features of URJA biomass downdraft gasifier system [Model URJA 10 PGD].

S. No.	Description	Specification
01	Type of gasifier	Close top downdraft gasifier
02	Biomass	Woody biomass
03	Rating of gasifier	10 kWe
04	Turn down ratio	1:3
05	Biomass conversion efficiency	75%
06	Gas composition	CO = 19 + 03% CH_4 = 03 + 1% H_2 = 18 + 02% CO_2 = 10 + 03% N_2 = 50 + 02%
07	Average calorific value of gas	1050 kcal/m^3
08	Material of construction	Hopper [IS 2062] Reactor boiler grate plate [SE 516] Ash drum [SS 304] Refractory [White heat K], Grate [SA 516] High temperate paint / Epoxy paint
09	Pumps and motors	All standard makes Kirlosker or equivalent
10	Control panel and instruments	Complete automated panel [Siemens]
11	Ash handling system	Automatic [continuous]
12	Safety arrangement	Rapture disc & water seals provided within the system
13	Gas flaring arrangement	Provided [Automated]
14	Structure & ladder	Structure & ladder / for operational convenience as per requirement
15	Auxiliary load	1 HP
16	Water requirement	50 litters /day [Maximum] [Evaporation & spillage loss] No water is discharged it is used in closed loop.
17	Maximum distance for consumer point from gasifier unit	20 ft.

2.4.2 Instrumentation:

While conducting the experiment, various equipment's are used to measure the input and output values of the setup. These equipment's are as follows:

2.4.2.1 Dual fuel running diesel engine:

It is a two-cylinder, four-stroke dual-fuelled diesel engine. Initially, the engine was started by primary fuel diesel, later on, secondary fuel producer gas is supplied through the air intake manifold. As the secondary fuel supplied, primary fuel consumption reduced which reflect the reduction in diesel consumption.

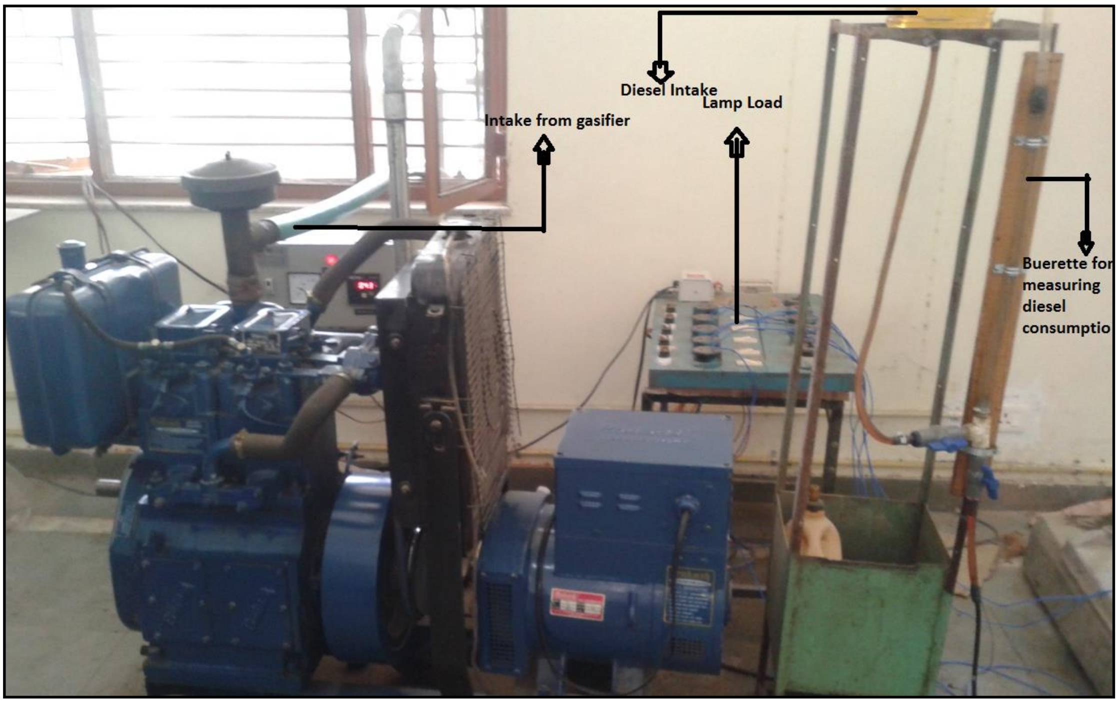


Figure 2.4: Dual fuel running diesel engine.

Technical specification are as follows:

Constant speed diesel engine.

Model : PV-14

Rated output: 14 B.H.P.

Rated speed : 1500 rev/min

S.F.C. : 251 gm/kW-Hr

Fuel : H.S. Diesel.

Lubrication oil grade: SAE 30/40/ Multigrade.

2.4.2.2 Gasifier control panel:

It contains following items:

a) Scrubber pump ON/OFF

b) Blower ON/OFF

c) Volt meter.

d) Temperature indication.

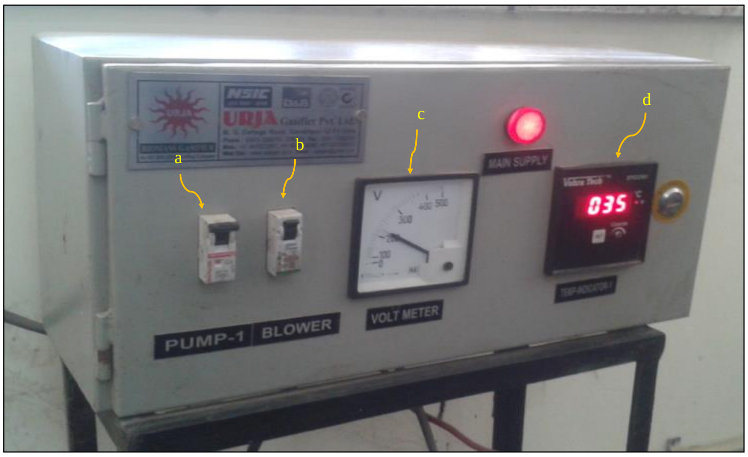


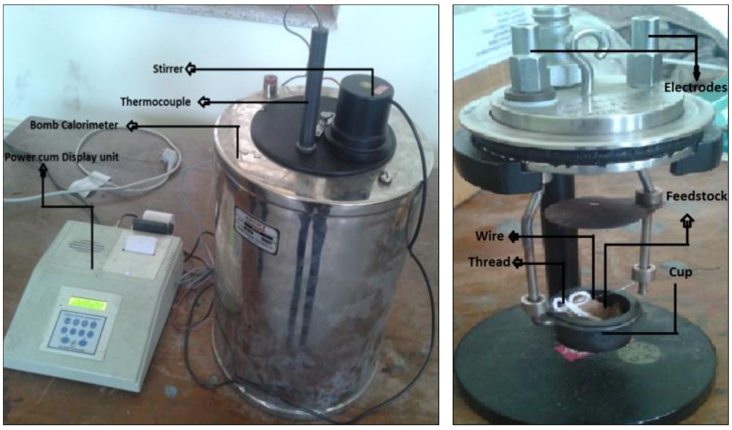
Figure 2.5: Main supply panel of downdraft gasifier system for operating pump and motor which is attached with gasifier system.

2.4.2.3 Gas chromatograph:

It is used to calculate the composition of the producer gas i.e., different gas included in it like CO, CO_2, CH_4, H_2, N_2 etc. The prob is inserted inside the ontlet of the producer gas to know the different composition available in the producer gas.

Figure 2.6: Gas chromatograph is used for measuring the different gas compounds present in the producer gas.

2.4.2.4 Bomb calorimeter:



(a) (b)

Figure 2.7: (a) Bomb calorimeter unit with display unit. (b) Combustion chamber unit of Bomb calorimeter. Equipment is used for calculating the calorific value of feedstock, Model- *BCM*, Voltage required- 230 V.

2.4.3 Experimental analysis:

Figure 2.8 shows the schematic diagram of the experimental setup installed at the ground floor, beside the Centre for Energy Resources and Development (CERD) building, Mechanical Engineering Department, IIT (BHU), Varanasi. The purpose of the experiment is to reduce the diesel fuel consumption by introducing the producer gas to run the dual fuel diesel engine. Solid biomass feedstock is used as a fuel in a downdraft gasifier system to produce the producer gas.

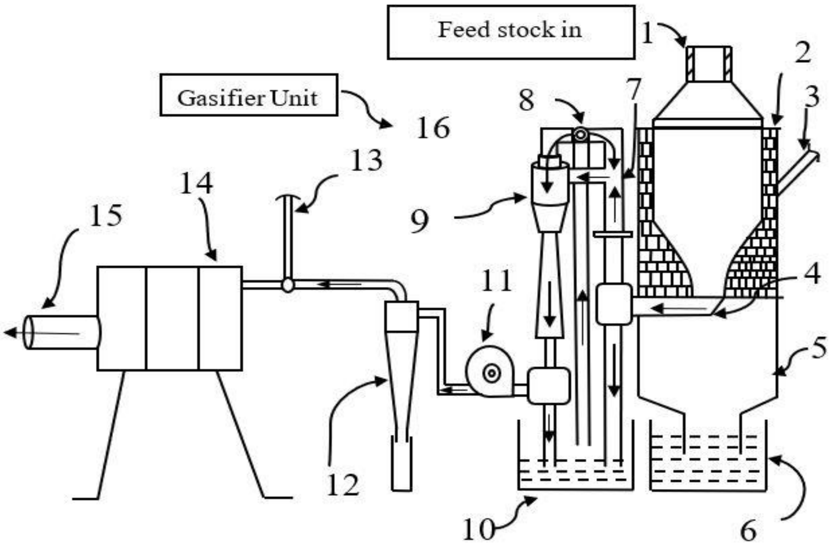


Figure 2.8: Schematic diagram of downdraft gasifier setup.

2.4.3.1 Procedure:

Initially, the gasifier setup was cleaned, tar, ash residuals and the remained charcoal pieces were also taken out of the system. The whole setup was washed. The bed and the grate were cleaned. In the present experiment wood and coconut shell were used as Bio-feedstock. The pellets of these feedstocks (25 *mm* × 25 *mm* in size) were feed through the hopper into the gasifier system. Gasifier top was closed with the water seal to prevent gas leakage. Once the gasifier starts producing quality gas, then quality gas is used as a fuel to run the diesel engine and start measuring the diesel consumption. At first, the engine is run only on diesel then immediate stopwatch starts to record time till engine consuming 20 *ml* diesel for a variable load of *0 kW* or no load, *1 kW*, *2 kW*, *3 kW* and *4 kW*. Afterwards, the engine is run on both diesel and producer gas combined and again the process is repeated for the same. Finally, we calculate diesel required to produce unit power in both conditions and it is noted that around 40 % of diesel consumption is saved. Cost analysis can also be done by calculating the cost required to produce *1kW-Hr* of energy in both the conditions and it is noted that cost required to produce *1kW-Hr* of energy is less in combined diesel and producer gas case.

Producer gas composition was noted down by using gas chromatographer. The gas flow rate was also noted by using the anemometer at the exit of the inbuilt filtration system. Thermocouple attached at the exit of the gasifier system to measure the gas outlet temperature.

2.4.3.2 Specification of solid biomass feedstock:

a) Coconut shell:

Downdraft gasifier system is best for producing low tar and using small size (25×25) *mm* solid biomass feedstock.

Figure 2.9: Coconut shell used as a solid biomass feedstock in downdraft gasifier system for obtained producer gas.

Varanasi is a well-known holy place for having Lord Baba Vishwanath as well as Hanuman Je Maharaj in Sankat Mochan temples. There are so many other old and great temples are also here who has a great history and therefore a huge amount of wet coconut is daily used for their Pujas & Arties and so, a large amount of coconut shells are available. In this regard, the coconut shell becomes a significantly major source of biomass feedstock, to be used in a downdraft gasifier system as a solid fuel.

Coconut shell Ultimate analysis	
C	50.22 %
H	5.7 %
O	43.37 %
N	0.22 %
Ash	0.71 %

Coconut shell Proximate analysis	
Moisture	10.1 %
Ash	14.2 %
Volatile	64.6 %
Fixed Carbon	11.2 %

Higher heating value = 14.881 MJ/kg.

b) Dalbergia Sisoo:

Dalbergia Sisoo is mostly used for packing heavy machinery parts or equipment and therefore after the procurement process of equipment and parts, huge amount of solid biomass is available in the Department of Mechanical Engineering IIT(BHU) which is further used as a fuel for downdraft gasifier system.

Figure 2.10: Dalbergia Sisoo used as a solid biomass feedstock in downdraft gasifier system for obtained producer gas.

Dalbergia Sisoo Ultimate analysis	
C	48.6 %
H	6.2 %
O	44.7 %
N	0.33 %
Ash	0.17 %

Dalbergia Sisoo Proximate analysis	
Moisture	8 %
Ash	0.55 %
Volatile	82.29 %
Fixed Carbon	17.16 %

Higher heating value = 13.046 MJ/kg.

2.4.4 Experimental observations:

The experiment has been performed in an I.C. engine lab, Department of Mechanical Engineering, IIT(BHU). The simple calculation is used for calculating the fuel consumption for a fixed load in both cases when only diesel and mixture of diesel with producer gas is used as a fuel to run the dual-fuel diesel engine. Moreover, cost analysis has also been done for calculating the money spend on 1 unit of energy production.

2.4.4.1 Observations:

Load estimation

- Internal load

Rating of pump = 0.5 HP

Rating of blower = 0.5 HP

Rating of diesel engine = 14 HP

- Total load applied

= Internal load + External load

= (0.5 HP + 0.5 HP + 14 HP) + External load attached

= 15 HP + External load attached

= 11.19 kW + External load attached (kW)

Following data were observed during experiments between time and 20 *ml* of diesel consumption at varying loads; *0 kW, 1 kW, 2 kW,3 kW* and *4 kW*. The diesel engine is run initially by only diesel then a mixture (producer gas with diesel). The producer gas is produced by the downdraft gasifier system when wood and coconut shell used alone one by one and then mixed with calcium oxide *(CaO)* 10% by weight then again used alone one by one as a solid fuel for the gasifier system. The observed data are mentioned in Table 2.3 to 2.7.

Table 2.3: Fuel consumption and time taken with increasing load when only diesel is used as fuel.

Only diesel used			
External load (kW)	Diesel consumption		Time taken (sec.)
	Initial burette reading (ml)	Final burette reading (ml)	
0	0	5	14
	5	10	26
	10	15	39
	15	20	52
1	0	5	10
	5	10	20
	10	15	31
	15	20	41
2	0	5	09
	5	10	18
	10	15	28
	15	20	37
3	0	5	09
	5	10	18
	10	15	27
	15	20	36
4	0	5	08
	5	10	15
	10	15	23
	15	20	32

Table 2.4: Fuel consumption and time taken with the increasing load when a mixture of diesel and producer gas is used as a fuel. Feedstock- Wood.

Diesel + Producer gas used			
Feedstock: Wood			
External load (kW)	Diesel consumption		Time taken (sec.)
	Initial burette reading (ml)	Final burette reading (ml)	
0	0	5	17
	5	10	35
	10	15	55
	15	20	75
1	0	5	17
	5	10	35
	10	15	53
	15	20	71
2	0	5	15
	5	10	31
	10	15	46
	15	20	63
3	0	5	15
	5	10	32
	10	15	44
	15	20	60
4	0	5	14
	5	10	28
	10	15	43
	15	20	55

Table 2.5: Fuel consumption and time taken with the increasing load when a mixture of diesel and producer gas is used as a fuel. Feedstock- Wood + 10 wt.% calcium oxide.

Diesel + Producer gas used			
Feedstock: Wood + 10 wt.% calcium oxide			
External load (kW)	Diesel consumption		Time taken (sec.)
	Initial burette reading (ml)	Final burette reading (ml)	
0	0	5	19
	5	10	38
	10	15	60
	15	20	81
1	0	5	18
	5	10	36
	10	15	54
	15	20	75
2	0	5	17
	5	10	31
	10	15	47
	15	20	64
3	0	5	14
	5	10	27
	10	15	44
	15	20	58
4	0	5	12
	5	10	22
	10	15	35
	15	20	49

Table 2.6: Fuel consumption and time taken with the increasing load when a mixture of diesel and producer gas is used as a fuel. Feedstock- Coconut shell.

Diesel + Producer gas used			
Feedstock: Coconut shell			
External load (kW)	Diesel consumption		Time taken (sec.)
	Initial burette reading (ml)	Final burette reading (ml)	
0	0	5	22
	5	10	40
	10	15	65
	15	20	90
1	0	5	19
	5	10	38
	10	15	58
	15	20	77
2	0	5	16
	5	10	31
	10	15	47
	15	20	65
3	0	5	14
	5	10	31
	10	15	47
	15	20	63
4	0	5	14
	5	10	25
	10	15	38
	15	20	56

Table 2.7: Fuel consumption and time taken with the increasing load when a mixture of diesel and producer gas is used as a fuel. Feedstock- Coconut shell + 10 wt.% calcium oxide.

Diesel + Producer gas used			
Feedstock: Coconut shell + 10 wt.% calcium oxide			
External load (kW)	Diesel consumption		Time taken (sec.)
	Initial burette reading (ml)	Final burette reading (ml)	
0	0	5	24
	5	10	47
	10	15	71
	15	20	95
1	0	5	21
	5	10	40
	10	15	61
	15	20	79
2	0	5	16
	5	10	33
	10	15	51
	15	20	67
3	0	5	15
	5	10	30
	10	15	45
	15	20	59
4	0	5	13
	5	10	26
	10	15	39
	15	20	52

Table 2.8 represents the summary of Table 2.3 to 2.7 for fuel consumption with respect to the time when only diesel is used versus diesel mixed with producer gas, to run the dual-fuelled diesel engine for power production.

Table 2.8: Fuel consumption for both diesel and mixture of diesel and producer gas with different load.

External load (kW)	Diesel consumption (ml)	Time taken (sec.)					
		Only diesel	Diesel + Producer gas				
			Wood	Wood + 10 wt.% CaO	Coconut shells	Coconut shells + 10 wt.% CaO
0	20	52	75	81	90	95
1	20	41	71	75	77	79
2	20	37	63	64	65	67
3	20	36	60	58	63	59
4	20	32	55	49	56	52

Followings graphs are drawn from the observed values which was taken during the experiments and mentioned in Table 2.3 to 2.7 or the summary of these in Table 2.8.

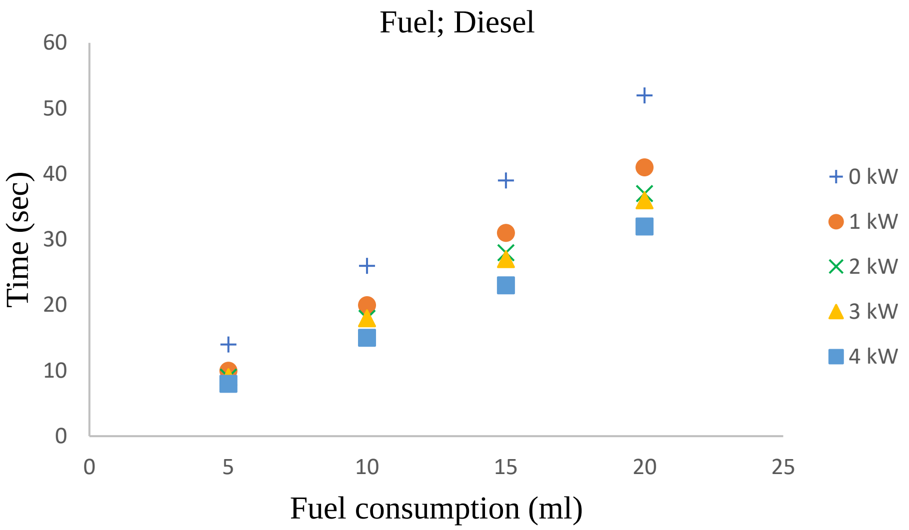


Figure 2.11: Shows the variation of Time Vs 20 *ml* diesel fuel consumption at varying loads; *0 kW*, *1 kW*, *2 kW*,*3 kW* and *4 kW*.

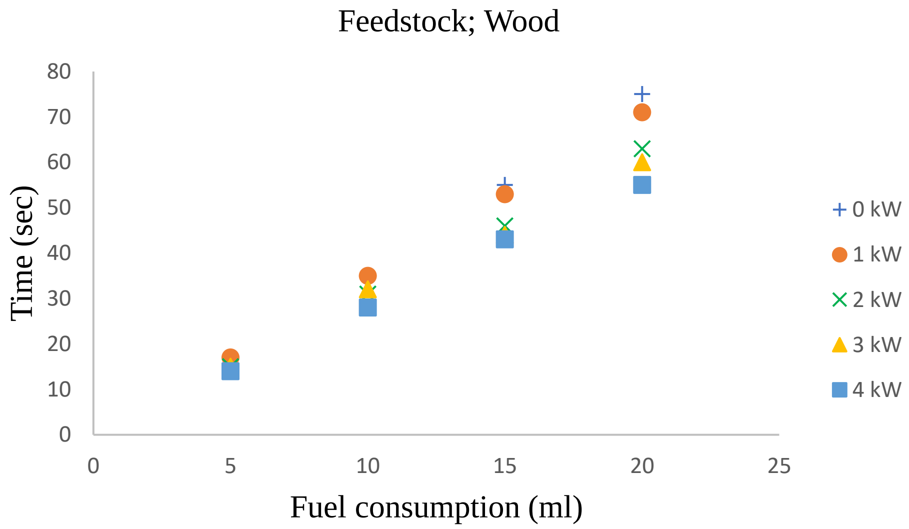


Figure 2.12: Shows the variation of time Vs 20 *ml* of diesel fuel consumption when producer gas is simultaneously supplied with diesel to run a dual-fuelled diesel engine at varying load; *0 kW*, *1 kW*, *2 kW*,*3 kW* and *4 kW*. Producer gas obtained from the wood feedstock.

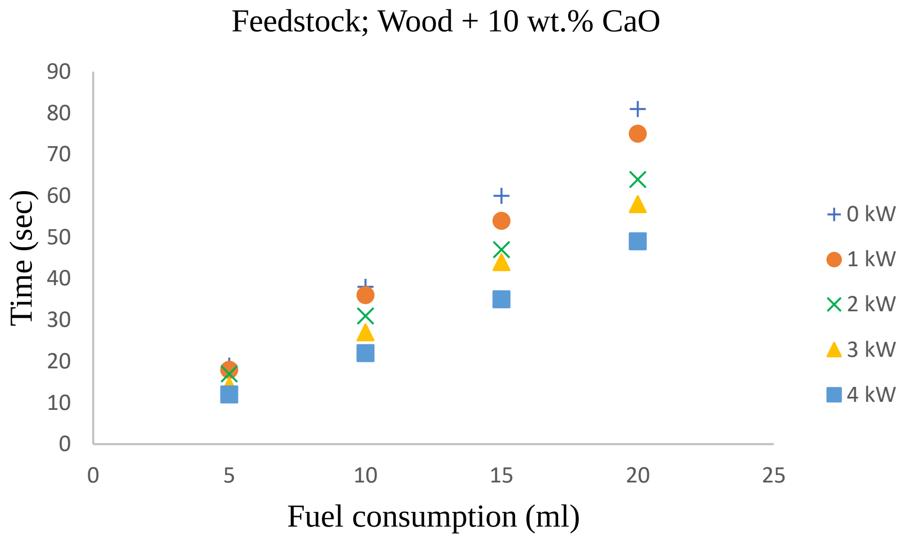


Figure 2.13: Shows the variation of time Vs 20 *ml* of diesel fuel consumption when producer gas is simultaneously supplied with diesel to run a dual-fuelled diesel engine at varying load; *0 kW*, *1 kW*, *2 kW*,*3 kW* and *4 kW*. Producer gas obtained from the wood + 10 wt.% *CaO* feedstock.

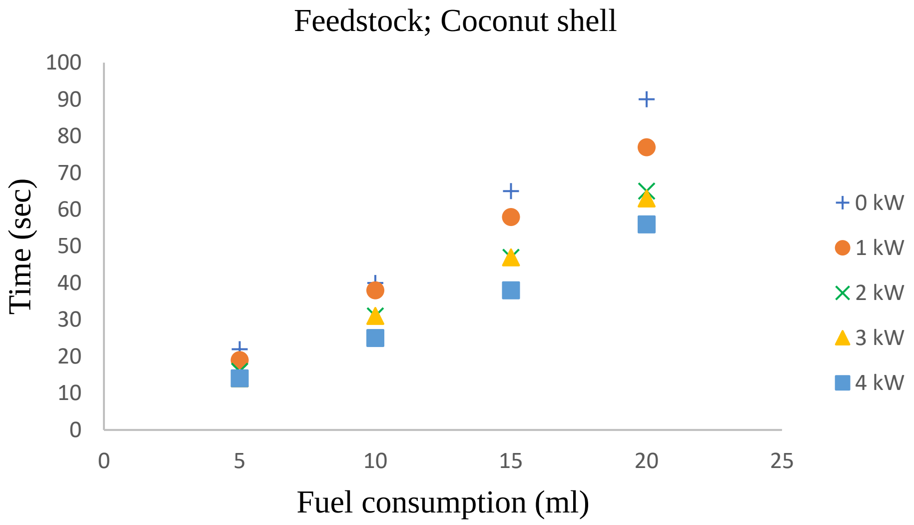


Figure 2.14: Shows the variation of time Vs 20 *ml* of diesel fuel consumption when producer gas is simultaneously supplied with diesel to run a dual-fuelled diesel engine at varying load; *0 kW*, *1 kW*, *2 kW*,*3 kW* and *4 kW*. Producer gas obtained from the coconut shell feedstock.

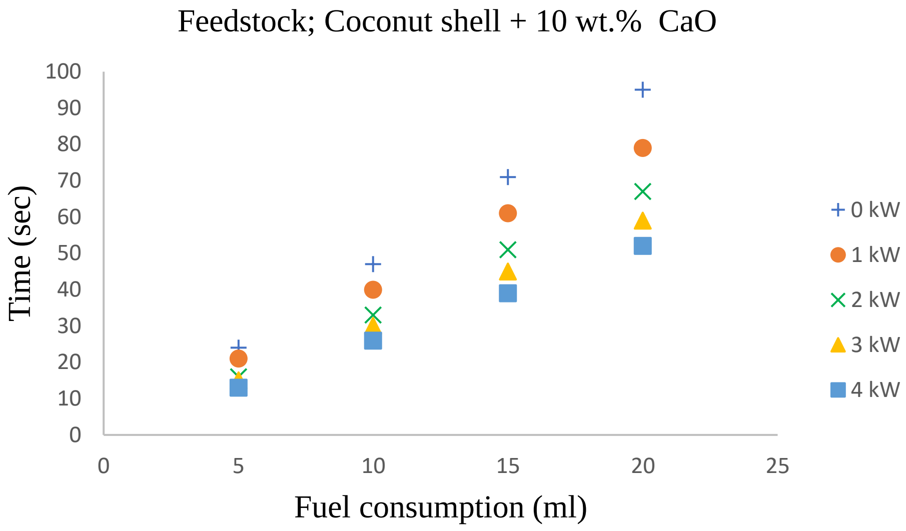


Figure 2.15: Shows the variation of time Vs 20 *ml* of diesel fuel consumption when producer gas is simultaneously supplied with diesel to run a dual-fuelled diesel engine at varying load; *0 kW*, *1 kW*, *2 kW*,*3 kW* and *4 kW*. Producer gas obtained from the coconut shell + 10 wt.% *CaO* feedstock.

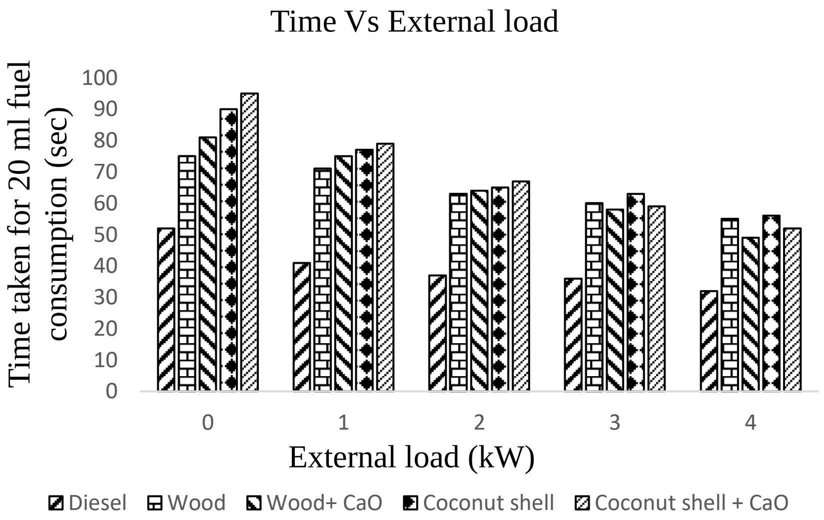


Figure 2.16 Shows the variation of time Vs external load for a fixed 20 *ml* fuel consumption.

Figure 2.11 to 2.15 is related to the time required to consume 20 *ml* of diesel fuel when only diesel and mixture of diesel with producer gas is used as a fuel to run the diesel engine. Producer gas is obtained from wood and coconut shell solid feedstocks.

In figure 2.11, only diesel is used as fuel to run the diesel engine at varying load; *0 kW, 1 kW, 2 kW, 3 kW* and *4 kW*. We found that at *0 kW* load the diesel engine takes 52 seconds to consume 20 *ml* of diesel and other loads it took 41, 37, 36, 32 seconds respectively. As the load increases, time got decreases for the same amount of diesel consumption at varying load.

In figure 2.12: Producer gas and diesel both used together as a fuel to run dual-fuelled diesel engine at varying load; *0 kW, 1 kW, 2 kW, 3 kW* and *4 kW*. We found that at *0 kW* load the diesel engine takes 75 seconds to consume 20 *ml* of diesel and other loads it took 71, 63, 60, 55 seconds respectively; therefore, we can say when producer gas is fed together with diesel, the 20 *ml* fuel consumption time increases. Hence diesel consumption decreases. Producer gas is obtained from the wood feedstock.

In figure 2.13: Calcium oxide 10% by weight is mixed with the wood feedstock. Calcium oxide is a type of catalyst that is used to remove tar from the producer gas. When producer gas and diesel both simultaneously used as a fuel to run the dual-fuelled diesel engine at varying load; *0 kW, 1 kW, 2 kW, 3 kW* and *4 kW*. We found that at *0 kW* load the diesel engine takes 81 seconds to consume 20 *ml* of diesel and other loads it took 75, 64, 58, 49 seconds respectively. The interesting point is mixing of *CaO* with feedstock give rise in time for the same amount of fuel consumption. It means as the tar reduces from the producer gas the quality of producer gas increases; as a result, more amount of diesel fuel is replaced by producer gas.

The same trend of the graph has been seen in figure 2.14 and figure 2.15, when coconut shell alone and then mixed with *CaO* 10% by weight is used as a solid feedstock to obtain producer gas. For *0 kW* load, diesel engine takes 90, 95 seconds respectively, to consume 20 *ml* fuel according to the figure number. On the whole, we can say as the gas quality increases the overall engine performance increases in terms of fuel consumption.

Figure 2.16, shows the variation between the time required to consume 20 *ml* fuel at external load; *0 kW*, *1 kW*, *2 kW*, *3 kW* and *4 kW* when the dual-fuelled diesel engine is run by only diesel and diesel with producer gas. It is clear from the graph that fuel consumption time increases when the diesel engine run by diesel with producer gas together. Also, producer gas obtained from different feedstock gives rise in time for consuming the same amount of fuel at the same external load.

2.4.4.2 Calculations:

a) **Calculation for calorific value;**

A bomb calorimeter is used for finding the calorific values of the feedstocks used for making producer gas.

- **Feedstock: Coconut shell;**

Mass of cup = 17.7188 gm

Mass of cup + coconut shell = 19.7677 gm

Mass of wire ($m_{w)}$ = 0.0110 gm

Mass of thread ($m_{t)}$ = 0.0173 gm

Mass of water ($m_{wt)}$ = 2 kg = 2000 gm

Change in temperature (ΔT) = 3.63^0C

Mass of coconut shell (m_{cs}) = 19.7677 - 17.7188 = 0.0173 gm

Calorific value of thread $(CV)_t$ = 4.12 kCal/mg

Calorific value of wire $(CV)_w$ = 0.335 kCal/mg

Specific heat of water (C_p) = 1kCal/kg

Change in enthalpy of water = Energy released from combustion of coconut shells + Energy released from combustion of thread + Energy released from combustion of wire.

$$m_{wt}\,C_{p\,wt}\,(\Delta T) = m_{cs}\,(CV)_{cs} + m_{th}\,(CV)_{t} + m_{w}\,(CV)_{w} \tag{2.5}$$

$2 \times 1 \times 3.63 \times 1000 = 2.0489 \times (CV)_{cs} + 0.0173 \times 4.12 + 0.0110 \times 0.335$

$(CV)_{cs} = 3543.33$ kCal/kg

$(CV)_{cs} = 3543.33 \times 4.187 =$ **14.881 kJ/kg**

- **Feedstock: Dalbergia Sisoo;**

Mass of cup = 17.7133 gm

Mass of cup + Dalbergia Sisoo = 18.9692 gm

Mass of wire ($m_{w)}$) = 0.0164 gm

Mass of thread ($m_{t)}$) = 0.0152 gm

Mass of water ($m_{wt)}$) = 2 kg = 2000gm

Change in temperature (ΔT) = 1.91^0C

Mass of Dalbergia Sisoo (m_{DS}) = 18.9692 - 17.7133 = 1.2559gm

Calorific value of thread $(CV)_t$ = 4.12 kCal/mg

Calorific value of wire $(CV)_w$ = 0.335 kCal/mg

Specific heat of water (C_p) = 1kCal/kg

Change in enthalpy of water = Energy released from combustion of Dalbergia Sisoo + Energy released from combustion of thread + Energy released from combustion of wire.

$$m_{wt}\,C_{p\,wt}\,(\Delta T) = m_{DS}\,(CV)_{DS} + m_{t}\,(CV)_{t} + m_{w}\,(CV)_{w} \tag{2.6}$$

$2 \times 1 \times 1.91 \times 1000 = 1.2259 \times (CV)_{DS} + 0.0152 \times 4.12 + 0.0164 \times 0.335$

$(CV)_{DS} = 3116.022$ kCal/kg

$(CV)_{DS}$ = 3116.002 × 4.187 = **13.046 MJ/kg**

b) Calculation of percentage reduction in diesel consumption:

A burette is fixed between the fuel supply to measure fuel consumption in both cases: When only diesel and diesel with producer gas is used to run the dual-fuel running diesel engine. The burette is marked from 0 to 20 *ml* and needs to count the time required to reach the marked point for the fixed external load when the diesel engine starts running.

- **For feedstock- wood;**

When only diesel is used, fuel consumed in 1 *sec* for *1 kW* external load = 20/41 *ml*.

When mixture of diesel and producer gas is used, fuel consumed in 1 *sec* for *1 kW* external load = 20/71 *ml*.

Percentage reduction in diesel consumption for;

1 kW external load = $\frac{\text{Only Disesl} - \text{Mixture}}{\text{Only Disesl}} \times 100$

$$= \frac{\frac{20}{41} - \frac{20}{71}}{\frac{20}{41}} \times 100 = \mathbf{42.25}\ \%$$

- **For feedstock- coconut shell;**

When mixture of diesel and producer gas is used, fuel consumed in 1 *sec* for *1 kW* external load = 20/77 *ml*.

Percentage reduction in diesel consumption for;

1 kW external load = $\frac{\text{Only Disesl} - \text{Mixture}}{\text{Only Disesl}} \times 100$

$$= \frac{\frac{20}{41} - \frac{20}{77}}{\frac{20}{41}} \times 100 = \mathbf{46.75}\ \%$$

Table 2.9 and Table 2.10 represents the summary of percentage (%) reduction of mixed fuel with respect to only diesel when wood and coconut shell used alone one by one and then mixed with Calcium oxide *(CaO)* 10% by weight as a solid fuel for the gasifier system to produce the producer gas.

Table 2.9: Percentage reduction in diesel consumption with respect to load. Feedstock-Wood, Wood with calcium oxide.

Feedstock: Wood			
External load (kW)	Diesel consumed in 1 sec.		Reduction in diesel $\frac{\text{Only diesel } - \text{Mixture}}{\text{Only diesel}} \times 100$
	Only diesel (ml)	Mixture of diesel and producer gas (ml)	
0	20/52	20/75	30.67%
1	20/41	20/71	42.25%
2	20/37	20/63	41.27%
3	20/36	20/60	40.00%
4	20/32	20/55	41.82%
Feedstock: Wood + 10 wt. % calcium oxide			
0	20/52	20/81	35.80%
1	20/41	20/75	45.33%
2	20/37	20/64	42.19%
3	20/36	20/58	37.93%
4	20/32	20/49	34.69%

Table 2.10: Percentage reduction in diesel consumption with respect to load.

Feedstock- Coconut shell, Coconut shell with calcium oxide.

Feedstock: Coconut shell			
External load (kW)	Diesel consumed in 1 Sec.		Reduction in diesel $\frac{\text{Only diesel } - \text{Mixture}}{\text{Only diesel}} \times 100$
	Only diesel (ml)	Mixture of diesel and producer gas (ml)	
0	20/52	20/90	42.22%
1	20/41	20/77	46.75%
2	20/37	20/65	43.08%
3	20/36	20/63	42.86%
4	20/32	20/56	42.85%
Feedstock: Coconut shell + 10 wt. % calcium oxide			
0	20/52	20/95	45.26%
1	20/41	20/79	48.10%
2	20/37	20/67	44.78%
3	20/36	20/59	38.98%
4	20/32	20/52	38.46%

c) Cost analysis:

In the cost analysis section, we find the money required for generating 1 unit of energy when producer gas is simultaneously used with the diesel to run the dual-fuelled diesel engine. Further, we compare our unit energy prices with the price of 1 unit of commercial electricity.

Cost of 1 litre diesel = Rs. 56.18 on May- June 2015.

Cost of 1 kg wood = Rs. 4 on May- June 2015.

Cost of 1 kg coconut shell = Rs. 3.5 on May- June 2015.

Cost of diesel in 1 second;

$$= \left(\frac{\text{Diesel consumed in 1 second} \times \text{Cost of 1 litter diesel}}{1000}\right)$$

Cost of wood used in 1 second;

$$= \left(\frac{\text{Wood used per hour} \times \text{Cost of wood per kg}}{1000}\right)$$

$$= \frac{8 \times 4}{3600} = \textbf{Rs 0.0088}$$

Cost of coconut shell used in 1 second;

$$= \left(\frac{\text{Coconut shell used per hr} \times \text{cost of coconut shell per kg}}{3600}\right)$$

$$= \frac{8 \times 3.5}{3600} = \textbf{Rs 0.0078}$$

Cost of 1-unit (1kW-Hr) energy;

$$= \left(\frac{\text{Total cost of fuel consumed in 1 second} \times 3600}{\text{Total load (kW)}}\right)$$

Table 2.11 and 2.12 shows the calculation detail for money spend on one unit of energy production when diesel and producer gas simultaneously used as a fuel to run a dual-fuelled diesel engine.

Table 2.11: Calculation of money spend on 1unit energy generation. Feedstock -Wood, Wood + 10 wt. % CaO

External load (kW)	Total load (kW)	Diesel consumed in 1 sec.		Cost of diesel consumed in 1 sec.		Total cost of fuel consumed in 1 sec.		Money spent on 1 unit of energy production	
		Only diesel (ml)	Diesel + producer gas (ml)	Only diesel (Rs)	Diesel + producer gas (Rs)	Only diesel (Rs)	Diesel + producer gas (Rs)	Only Diesel (Rs)	Diesel + producer gas (Rs)
Feedstock: Wood									
0	11.19	20/52	20/75	0.0216	0.0149	0.0216	0.0237	6.95	7.62
1	12.19	20/41	20/71	0.0274	0.0158	0.0274	0.0246	8.09	7.26
2	13.19	20/37	20/63	0.0304	0.0178	0.0304	0.0266	8.30	7.26
3	14.19	20/36	20/60	0.0312	0.0187	0.0312	0.0275	7.92	6.98
4	15.19	20/32	20/58	0.0351	0.0194	0.0351	0.0282	8.32	6.68
Feedstock: Wood + 10 wt. % CaO									
0	11.19	20/52	20/81	0.0126	0.0138	0.0126	0.0226	6.95	7.27
1	12.19	20/41	20/73	0.0274	0.0154	0.0274	0.0242	8.09	7.15
2	13.19	20/37	20/55	0.0304	0.0204	0.0304	0.0292	8.30	7.97
3	14.19	20/36	20/48	0.0312	0.0234	0.0312	0.0322	7.92	8.17
4	15.19	20/32	20/47	0.0351	0.0239	0.0351	0.0327	8.32	7.75

Table 2.12: Calculation of money spend on 1unit energy generation. Feedstock: Coconut shells, Coconut shells + 10 wt. % CaO

External load (kW)	Total load (kW)	Diesel consumed in 1 sec.		Cost of diesel consumed in 1 sec.		Total cost of fuel consumed in 1 sec.		Money spent on 1 unit of energy production	
		Only diesel (ml)	Diesel + producer gas (ml)	Only diesel (Rs)	Diesel + producer gas (Rs)	Only diesel (Rs)	Diesel + producer gas (Rs)	Only diesel (Rs)	Diesel + producer gas (Rs)
Feedstock: Coconut shells									
0	11.19	20/52	20/90	0.0216	0.0125	0.0216	0,0203	6.95	6.53
1	12.19	20/41	20/77	0.0274	0.0146	0.0274	0.0224	8.09	6.62
2	13.19	20/37	20/65	0.0304	0.0173	0.0304	0.0251	8.30	6.85
3	14.19	20/36	20/63	0.0312	0.0178	0.0312	0.0256	7.92	6.49
4	15.19	20/32	20/56	0.0351	0.0200	0.0351	0.0278	8.32	6.59
Feedstock: Coconut Shells + 10 wt. % CaO									
0	11.19	20/52	20/95	0.0216	0.0118	0.0216	0.0196	6.95	6.31
1	12.19	20/41	20/79	0.0274	0.0142	0.0274	0.0220	8.09	6.50
2	13.19	20/37	20/67	0.0304	0.0168	0.0304	0.0246	8.30	6.71
3	14.19	20/36	20/59	0.0312	0.0190	0.0312	0.0268	7.92	6.84
4	15.19	20/32	20/52	0.0351	0.0216	0.0351	0.0294	8.32	6.97

Followings graphs are drawn using the calculated values which are mentioned in Table 2.9 to 2.12. The graphs are related to the percentage reduction in diesel consumption and cost analysis between commercial electricity vs our energy production for unit energy.

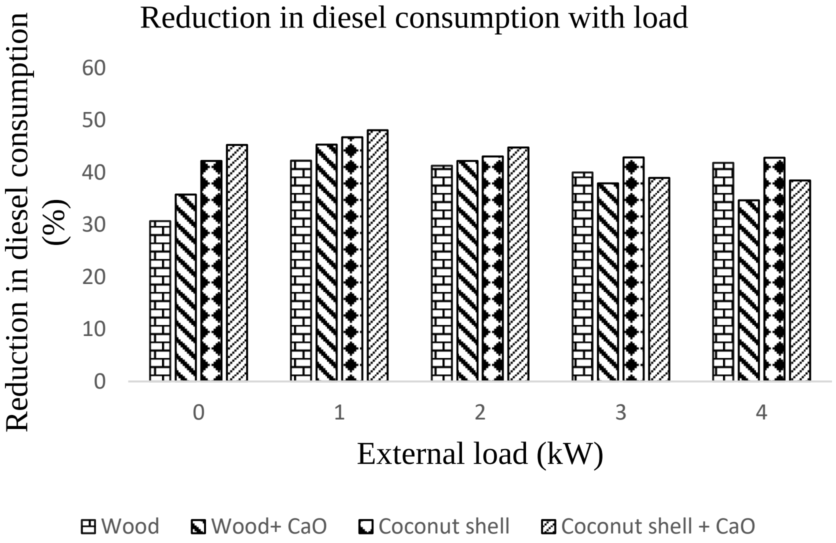


Figure 2.17 Shows the variation between the % reduction in diesel consumption Vs external varying load; *0 kW, 1 kW, 2 kW, 3 kW* and 4 *kW*. Producer gas is obtained from wood, wood + 10 wt. % *CaO*, Coconut shell and Coconut shell + 10 wt. % *CaO*.

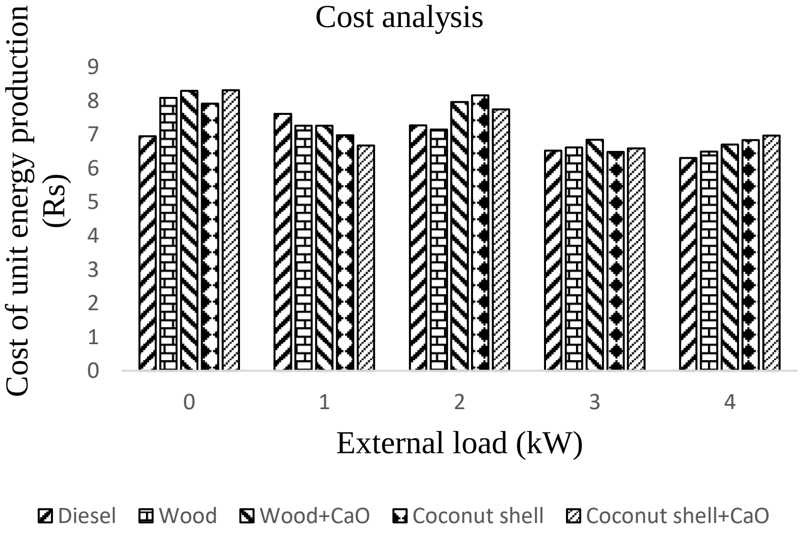


Figure 2.18 Shows the cost of unit energy production when dual fuelled diesel engine run by diesel, diesel with producer gas at varying external load; *0 kW, 1 kW, 2 kW, 3 kW* and

4 kW. The producer gas obtained from wood, wood + 10 wt. % *CaO*, Coconut shell and Coconut shell + 10 wt. % *CaO*.

In figure 2.17, dual-fuelled diesel engine is initially run by only diesel, and we count the time required for consuming 20 *ml* of diesel at varying external load; *0 kW, 1 kW, 2 kW, 3 kW* and *4 kW*. We then use the producer gas along with diesel as a fuel to run the engine at the same conditions. As a result, we found that at 0 *kW* or no-load condition when diesel engine run by diesel with producer gas (producer gas obtained from wood) the 30.67% diesel is replaced by producer gas. For the other load conditions, the reduction in diesel consumption is 42.25%, 41.27%, 40.00% and 41.82% respectively, while producer gas obtained from wood+ 10 wt. % *CaO*, Coconut shell, Coconut shell + 10 wt. % *CaO*, respectively. The fluctuation in percentage reduction occurs due to the quality of producer gas. As the producer gas quality deteriorates, the diesel consumption affected, which results in variation in percentage reduction.

In figure 2.18, we present the money spend on fuel to produce electricity. From the calculation, we found the expenditure of unit energy production is Rs. 6.95 when only diesel is used to run the dual-fuelled diesel engine at *0 kW* load or no-load condition. For the other external loads; *1 kW, 2 kW, 3 kW* and *4 kW* the expenses are Rs. 8.09, Rs. 8.30, Rs. 7.92 and Rs. 8.32 respectively. Here we can see the unit energy cost increases when external load increases. As we know, as the load increases, fuel consumption increases; therefore, unit energy cost increases.

Further, we found unit energy cost Rs. 7.62 for external load *0 kW* when producer gas (Feedstock – wood used to obtain producer gas) along with diesel is used. For the other external loads; *1 kW, 2 kW, 3 kW* and *4 kW* the expenses are Rs. 7.26, Rs. 7.26, Rs. 6.98 and Rs. 6.68 respectively. Viewing the above costs, we can say producer gas reduces the diesel consumption, whose effect reflects in the unit energy production prices. The unit energy production cost got decreased by Rs. 0.83, Rs. 1.64 for external load *1 kW* and *4 kW* respectively, compared to diesel.

In addition, when wood + 10 wt.% *CaO* used, the unit energy production cost is Rs. 7.27 for external load *0 kW*. For the other external loads; *1 kW, 2 kW, 3 kW* and *4 kW* the expenses are Rs. 7.15, Rs. 7.97, Rs. 8.17 and Rs. 7.75 respectively. Here the addition of *CaO* with biomass feedstock reduces the tar presence in producer gas, on the other hand, producer gas quality increases which lowered the unit energy production cost, which is Rs. 0.94, Rs. 0.57 for external load *1 kW* and *4 kW* respectively, compared to diesel. In addition, while doing comparison between wood and wood 10 wt. % *CaO* at external loads *1 kW* and *4 kW*. We found that at lower load *(1 kW), CaO* works, and unit energy production cost got reduced by Rs. 0.11, but at a higher load *(4 kW)* the unit energy production cost got increased by Rs. 1.07 this increment in price due to the loss of *CaO* effect.

Furthermore, for *0 kW* external load, the unit energy production cost is Rs. 6.53 and Rs. 6.31 when producer gas (Feedstock - coconut shell, coconut shell + 10 wt. % *CaO*, used one by one to obtained producer gas) along with diesel is used to run a dual-fuelled diesel engine. For the other external loads; *1 kW, 2 kW, 3 kW* and *4 kW* the expenses are Rs. 6.62, Rs. 6.85, Rs. 6.49, Rs. 6.59 respectively, belongs to coconut shell and Rs. 6.50, Rs. 6.71, Rs. 6.84, Rs. 6.97 respectively, belongs to coconut shell + 10 wt. % *CaO*. The unit energy production cost got reduced by Rs. 1.47, Rs. 1. 73 belongs to coconut shell for external load *1 kW* and *4 kW* respectively, compared to diesel. Also, Rs. 1.59, Rs. 1. 35 belongs to coconut shell + 10 wt % *CaO* for external load *1 kW* and *4 kW* respectively, compared to diesel. On the other hand, while doing comparison between coconut shell and coconut shell + 10 wt. % CaO at external loads *1 kW* and *4 kW*. We found at lower load *(1 kW)*, CaO works, and unit energy production cost got reduced by Rs. 0.12, but at a higher load *(4 kW)* the unit energy production cost got increased by Rs. 0.38 this increment in price due to the loss of CaO effect.

2.5 Needs for cleaning producer gas

Raw producer gas having lots of impurities like - tar, dust particles, ash and pollutant gas etc. these impurities create severe problems in the diesel engine when producer gas is used as a gaseous fuel; therefore, suitable techniques needs to be used for reducing the impurities present in the producer gas. We used primary filtration method for tar elimination.

2.5.1 Tar:

Tars are all organic compounds except gaseous hydrocarbons $(C_1\text{-}C_6)$ which are present in the producer gas. However, the tar composition depends on the type of fuel and the gasification process. A variety of classifications for tar are found in the literature. These classifications in general are based on: properties of the tar components, and the producer gas application. The tar components based on their chemical, condensation and solubility behaviour can be classified into five classes, as given in Table 2.13 [7].

One of the main technical barriers in biomass gasification development is the presence of tars in the fuel gas. These tars can cause several problems, such as cracking in the pores of filters, forming coke, and condensing in the cold spots. The high concentration of tars can damage or requires high maintenance for engines and turbines. Moreover, these tars contain large amounts of energy which should be converted to the fuel gas as H_2, CO, CH_4, etc. The tar levels and composition changes with gasifier type, process conditions, and biomass type. Tars can be removed by physical (e.g., scrubbing), non-catalytic (e.g. thermal cracking), and catalytic tar removal processes.

Table 2.13: Classification of tar compounds [7].

Tar classes	Classification	Tar compounds	Tar dew points
Class 1	GC- undetectable	Very heavy polyaromatic compounds,7 or more rings.	Very high tar dew point, actual temperatures and concentrations are not known.
Class 2	Heterocyclic aromatics	Cyclic hydrocarbons with heteroatoms, highly water soluble e.g. phenol, cresol and pyridine.	$< -50\ ^{0}$C at 10000 mg Nm^{-3}
Class 3	Light aromatic	Compounds that usually do not cause problems as a result of condensation or water solubility e.g. toluene, strene and xylene.	$< -50\ ^{0}$C at 10000 mg Nm^{-3}
Class 4	Light polyaromatic	2 and 3 ring compounds that condenses at intermediate temperatures at relatively high concentrations e.g. naphthalene, phenanthrene and anthracene.	$> 10\ ^{0}$C at ≥ 1 mg Nm^{-3}
Class 5	Heavy polyaromatic	4-6 ring compounds that condense at high temperature and low concentrations e.g. fluoranthene, pyrene.	$\geq 120\ ^{0}$C at 0.1 mg Nm^{-3}

2.5.1.1 Tar removal approaches:

Generally, two approaches: Primary method and Secondary method are used for Tar removal.

- Primary method: It is a method which is employed inside the gasifier and does not require any secondary reactor for the elimination of tar. Catalyst is mixed with the biomass feedstock inside the gasifier system. As the catalyst reached its activation temperature, it starts working, and a significant amount of tar has been removed from the producer gas before leaving the gasifier system itself.
- Secondary method: In this method, a separate reactor is used to reduce the tar content in producer gas. Secondary tar cleaning techniques belong to both wet and hot gases.

In this section, we are interested in primary method for tar removal from the producer gas, produced from the downdraft gasifier system.

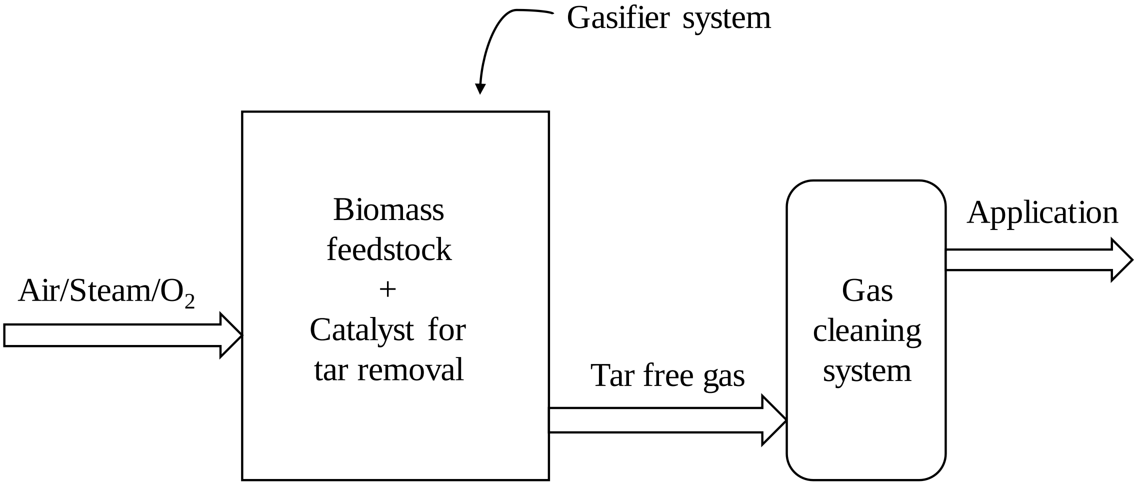


Figure 2.19: Primary method used for tar reduction [8].

In general, tars are removed by physical, non-catalytic (e.g., thermal cracking), and catalytic tar reduction processes. Catalytic tar conversion is an interesting approach for gas cleaning. Such an approach is interesting because it possesses the potential to increase conversion efficiencies and eliminating the need for the disposal of tars. The catalytic conversion of tars is usually known as hot gas cleaning. The research on catalytic tar conversion involves two methods:

- One approach involves mixing catalyst with the biomass feedstock, also called in situ. In this method, tar is reduced in the gasifier itself.
- In the second approach, the producer gas is cleaned in a secondary reactor. [9]

2.5.1.2 Classification of catalyst:

The catalysts used for tar reduction are divided into two classes on the basis of their production method: Mineral and Synthetic catalysts.

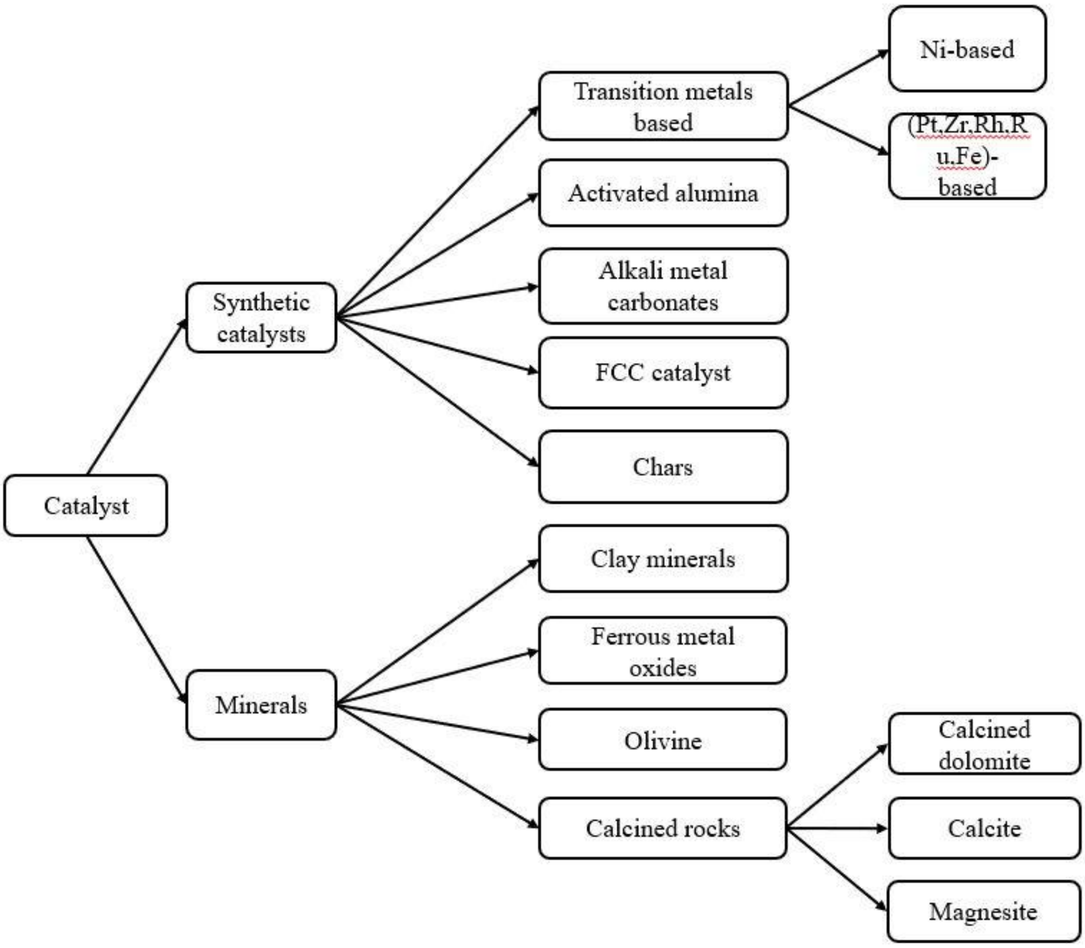


Figure 2.20: Classification of catalysts. [7]

a) Minerals:

They are naturally occurring. Minerals have definite chemical composition and also an ordered atomic arrangement. The catalysts in this class are available in nature and can be used directly. In general, mineral catalysts are cheaper than synthetic catalysts. [7]

- **Calcined rocks-** Alkaline earth metal oxides *(CaO and/or MgO)* come under this category. The classification is done according to *CaO /MgO* ratio. The catalytic activity can be increased by increasing *Ca/Mg* ratio, decreasing grain size and increasing the active metal content. The main factor causing deactivation of calcined rocks are coke formation. Coke causes deactivation of the calcined rocks by covering their active sites and blocking their pores. Advantages are that they are inexpensive and abundant. They attain high tar conversion ~ 95% conversions with dolomite. Disadvantages are fragile materials and quickly eroded. [7]

2.5.1.3 Methodology:

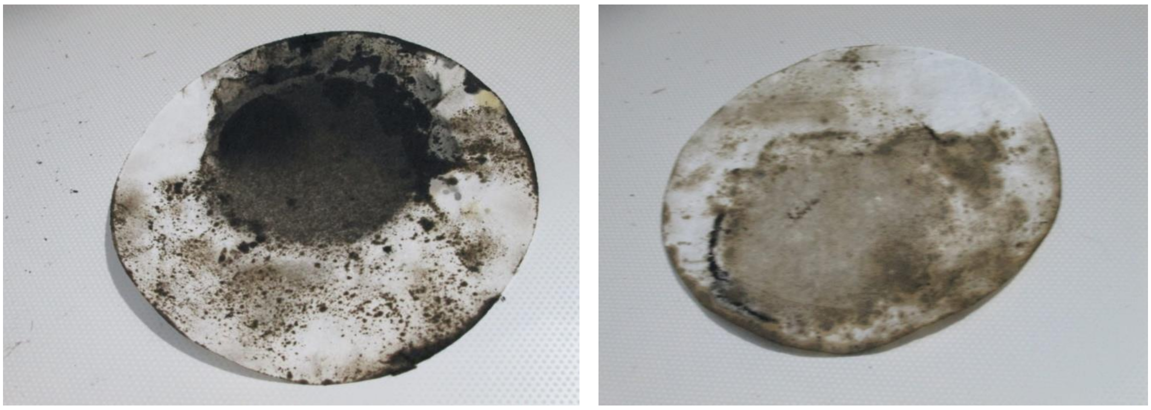
In the present study, minerals catalyst calcium oxide *(CaO)* has been used which comes under calcined rocks, also known as Alkaline earth metal oxides *(CaO and/or MgO)*. The *CaO*, 10% by weight, is mixed with the biomass feedstock inside the gasifier system. As the gasifier inside temperature reaches the catalyst activation temperature, tar reduction process starts, and significant tar has been eliminated from the producer gas. The samples of tar were taken using filter paper at the outlet of the gasifier system in both conditions; only feedstock and feedstock with *CaO* 10% by weight. The difference in weight of the sample papers confirmed the reduction of tar from the producer gas leaving from the gasifier system. Dalbergia Sisoo and coconut shell have been used as a solid biomass feedstock for the study. The details of these feedstocks have been already discussed in section 2.4.3.2.

2.5.1.4 Observations and analysis:

Minerals calcium oxide *(CaO)* used as a catalyst for tar reduction in producer gas. We use the primary method for tar reduction in which 10 % by weight *CaO* is mixed with the biomass feedstock. Tar weight is measured by placing the filter paper at the outlet of the gasifier system before and after mixing catalyst with the feedstock. The difference in weight of filter paper gives the reduction of tar. In figure 2.21-22, we present the photo of filter paper containing tar when producer gas obtained from feedstock; wood, wood + 10 wt. % *CaO* and coconut shell, coconut shell + 10 wt. % *CaO*.

(a) (b)

Figure 2.21: (a) Filter paper containing tar, feedstock- Wood. (b) Filter paper containing tar, feedstock- wood + 10 wt.% *CaO*.



(a) (b)

Figure 2.22: (a) Filter paper containing tar, feedstock- Coconut shell. (b) Filter paper containing tar, feedstock- Coconut shell + 10 wt.% *CaO*.

In figure 2.23, the tar reduction is seen by mixing CaO as a catalyst with biomass feedstock. During the experiments, we found the weight of tar is 0.154 *gm/min* and 0.0798 gm/min, which belongs to wood and wood + 10 wt. % CaO. The difference in these weight gives the tar reduction, which is 0.0742 gm/min or percentage of tar reduction is 48.18% at 850^{o}C. Similarly, for coconut shell and coconut shell + 10 wt. % CaO, the filter paper weight is 0.125 *gm/min* and 0.116 *gm/min*. The difference in the weight gives the tar reduction, which is 0.009 *gm/min* or the percentage of tar reduction is 7.2% at 790^{o}C.

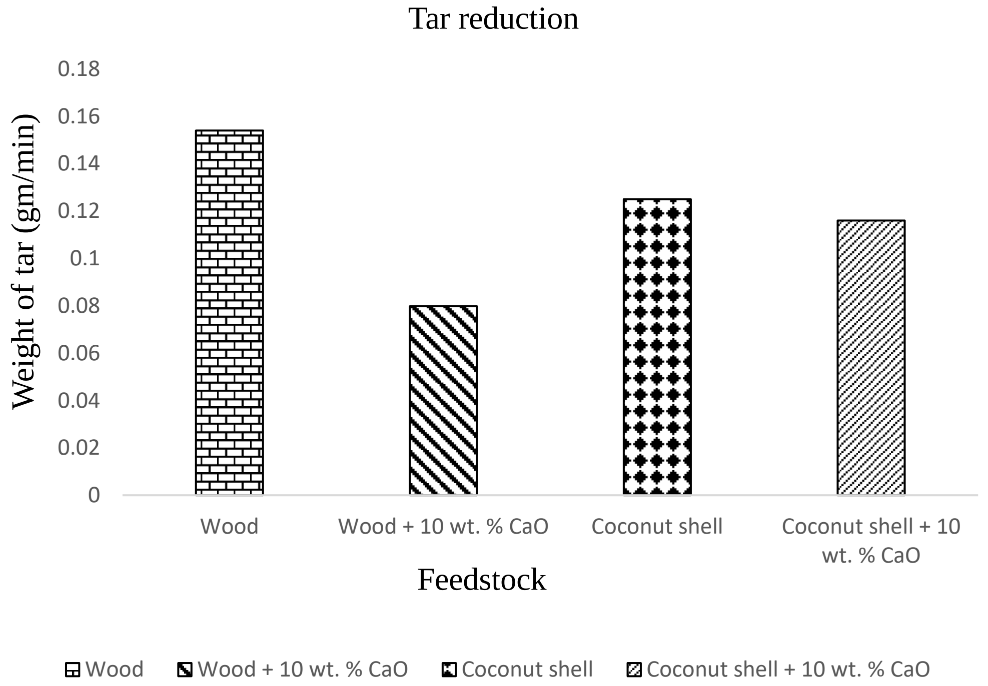


Figure 2.23: Shows the tar reduction *(gm/min)* when calcium oxide (as a catalyst) is mixed with the feedstock – Wood, Wood + 10 wt. % CaO and Coconut shell, Coconut shell + 10 wt. % CaO.

Main reasons for tar formation are:

a) Presence of carbon, moisture and ash particle in the feed stock

b) Extent of combustion

Although, the percentage of carbon, moisture and ash particles is more in coconut shell in comparison to the wood for the same rate of air suppled to the combustion chamber, but majority of the mass of coconut shell is burnt completely as compared to the wood and therefore less amount of tar generated in the coconut shell. Moreover, the addition of 10% CaO does not significantly help to reduce the tar content of Coconut shell in comparison to Wood because of the formation of Carbide (CaC_2) which add more ash to the final product. Since the percentage of carbon is more in the case of coconut shell (50.22%) as compare to the wood (48.6%), addition of CaO does not add more to the performance of tar reduction.

2.6 Uncertainty analysis

A complete uncertainty analysis performed on the experimental data taken on May- June 2015 mentioned in Table 2.3 to 2.7. The analysis takes into account the uncertainties in measured parameters like load, time and fuel consumption for different feedstocks which are mentioned in Table 2.14. Although, the uncertainty has been analysed at the different load conditions; *0 kW, 1 kW, 2 kW, 3 kW* and *4 kW* for the different feedstocks as shown in Table 2.14, for the load *4 kW* the uncertainty has been observed for only diesel is 8 ± 0.81 as shown in figure 2 which is calculated with the help of equation (2.9). Moreover, the uncertainty associated with the different feedstocks like wood, wood + 10 wt. % CaO, coconut shell and coconut shell + 10 wt. % CaO at the load *4 kW* are 13.75 ± 1.25, 12.25 ± 1.70, 14 ± 2.94, and 13 ± 00 respectively.

$$R = f(X_1, X_2, X_3, \ldots\ldots\ldots X_N) \tag{2.7}$$

where, R is any function of variable X.

$$\sigma_R = f(\sigma_{X1}, \sigma_{X2}, \ldots\ldots \sigma_{XN}) \tag{2.8}$$

where, σ_R = Uncertainty in R.

$$\sigma_R = \sqrt{\sum_{i=1}^{N}\left(\frac{\partial R}{\partial X_I}\ \partial X_i\right)^2} \tag{2.9}$$

$$U_R = \pm\sqrt{\frac{1}{R^2}\left(\sum_{i=1}^{N}\left(\frac{\partial R}{\partial X_I}\ \partial X_i\right)^2\right)} \tag{2.10}$$

where, U_R = Relative uncertainty

Table 2.14: Uncertainty analysis for different feed stokes at different load conditions.

Load (kW)	Uncertainty analysis for different feedstocks				
	Diesel	Wood	Wood + 10 wt. % CaO	Coconut shell	Coconut shell + 10 wt. % CaO
0	13±0.81	18.75±1.5	20.25 ± 1.5	20.5 ± 3.31	23.75 ± 0.5
1	10.25±0.5	17.75±0.5	18.75 ± 1.5	19.25 ± 0.5	19.75 ± 1.5
2	9.25±0.5	15.75± 0.95	16 ± 1.41	16.25 ± 1.25	16.75 ± 0.95
3	9±0.00	15 ± 2.16	14.5 ± 1.73	15.75 ± 1.25	14.75 ± 0.5
4	8±0.81	13.75± 1.25	12.25 ± 1.70	14 ± 2.94	13 ± 0.0

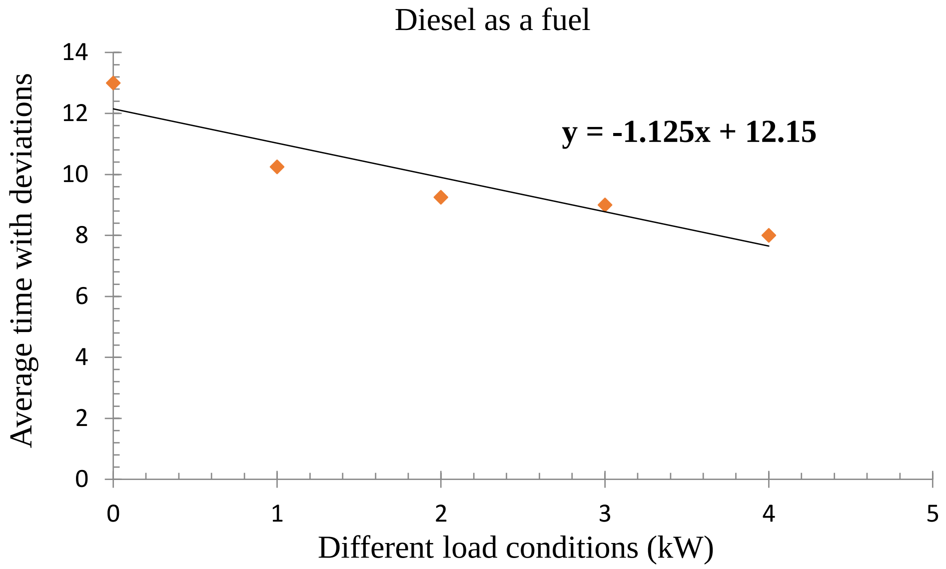


Figure 2.24: Shows the average time taken for diesel consumption at different load conditions. The plot in figure 2.24 describes the average time taken with uncertainty at different load conditions. This graph also suggests that the average time decreases with the increasing load. The best-suited curve for these variations is y = - 1.125x + 12.15.

2.7 Conclusions

In this chapter, we focused on the quality of producer gas in terms of fuel consumption at varying load capacities. Also, we discussed the effect of producer gas when used with diesel fuel for power production. In addition, we also discussed tar removal method.

In the first case, we carried out experiments at *1 kW* external load with diesel, for *20 ml* of fuel consumption the engine takes 41 second and Rs. 8.09 spent on unit energy production.

In the second case, the load remains same, only diesel with producer gas (producer gas obtained from wood feedstock) is used, for the same amount of fuel consumption engine takes 71 seconds and unit energy production cost is Rs. 7.26.

In the third case, the wood feedstock is mixed with 10 wt. % *CaO* to obtain producer gas which is supplied together diesel, the engine takes 75 seconds for the same amount of fuel consumption and unit energy production cost is Rs. 7.26.

In the fourth case, diesel with producer (producer gas obtained from coconut shell feedstock) is used, the engine takes 77 seconds for 20 *ml* fuel consumption, and unit energy production cost is Rs. 6.62.

In the fifth case, the coconut shell feedstock is mixed with 10 wt. % *CaO* to obtain producer gas which is supplied together diesel, the engine takes 79 seconds for the same amount of fuel consumption and unit energy production cost is Rs. 6.50.

It is clear from the above results that the fuel consumption time increases while using producer gas with diesel for the same amount of fuel consumption and hence the diesel consumption reduces as well as the cost for unit energy production.

In addition, we performed experiment for tar removal from producer gas. We used mineral catalyst calcium oxide for tar removal by using the primary filtration method.

The 10 wt. % *CaO* is mixed with biomass feedstock inside the gasifier system. The 0.0742 *gm/min* or percentage of tar reduction is 48.18% at 850^{o}C while using *CaO* with wood feedstock. Similarly, 0.009 *gm/min* or the percentage of tar reduction is 7.2% at 790^{o}C when *CaO* mixed with a coconut shell. After the primary filtration method, some tar still remains with the producer gas, which needs to be removed.

Moreover, the uncertainty analysis has been done using experimental data mentioned in Table 2.3 to 2.7. The uncertainty for *4 kW* load for diesel fuel is 8 ± 0.81.

In chapter - 4, a secondary filtration system has been designed, and we performed numerical analysis for selecting the best parameters, which significantly help to predict the best filtration designs.

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