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A dual fired downdraft gasifier system to produce cleaner gas for power generation: Design, development and performance analysis

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ABSTRACT

The existing biomass gasifier systems have several technical challenges, which need to be addressed. They are reduction of impurities in the gas, increasing the reliability of the system, easy in operation and maintenance. It is also essential to have a simple design of gasifier system for power generation, which can work even in remote locations. A dual fired downdraft gasifier system was designed to produce clean gas from biomass fuel, used for electricity generation. This system is proposed to overcome a number of technical challenges. The system is equipped with dry gas cleaning and indirect gas cooling equipment. The dry gas cleaning system completely eliminates wet scrubbers that require large quantities of water. It also helps to do away with the disposal issues with the polluted water. With the improved gasifier system, the tar level in the raw gas is less than 100 mg Nm^{-3}.Cold gas efficiency has improved to 89% by complete gasification of biomass and recycling of waste heat into the reactor. Several parameters, which are considered in the design and development of the reactors, are presented in detail with their performance indicators.

1. Introduction

Global energy consumption has increased in the year 2010 after a downturn in the year 2009 [1]. The primary energy consumption alone grew by 5.6% during the year 2010. It is the strongest growth since 1973 [2]. It is important to ensure adequate power supply for a sustainable economic growth rate of more than 8% per year. Biomass fuel is one of the potential resources to produce electricity and to meet the growing energy demand in India. About 78 million rural households in India do not have access to the grid [3]. In the year 2005, the Ministry of Power launched one of its flagship programs – Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY). The objective of this program is to provide access to electricity to the dwellers of 1.20 lakh un-electrified villages. This program also aims to provide free electricity to 2.34 crores of rural households living below the poverty line. In the year 2012 the program has achieved more than 87.5% of the target. Under this initiative the per capita energy consumption envisaged, is in the order of 50 kWh per person per annum. This is far below the national average per capita energy consumption, which is at the tune of 400 kWh [4]. This is a clear indicator of a huge deficit to be met in the immediate future. So, there is an urgent need to have an alternative source of power to improve the current scenario. Biomass fuel is one of the potential sources of energy, which can be used to produce power even in remote locations.

Biomass fuel is converted into gaseous fuel through a thermochemical process. In this process gaseous fuel is produced from biomass by partial combustion [5–7]. The combustible gas produced from biomass is known as producer gas. The producer gas consists of a mixture of combustible and non-combustible gases. The combustible fraction consists of hydrogen (H_2), carbon monoxide (CO) and methane (CH_4). The non-combustible fraction consists of carbon dioxide (CO_2), nitrogen (N_2) and moisture (H_2O). This producer gas can be used as a fuel in a furnace as an alternate heat source for industrial heating applications. The producer gas can be supplied to an internal combustion engine to produce electricity. Use of biomass gasification for electricity generation is presented in Ref. [8]. This paper brings out several challenges related to the impurities in gas and cleaning technologies. The tar and dust content in the gas and challenges related to the existing gas cleaning processes are acting as barriers. In order to overcome the barriers, key parameters that have greater influence on system performance were identified. Based on the identified key parameters different gasifier designs were compared and analyzed in details. This research work is focused to design and develop an efficient gasifier system to produce clean gas, which is suitable for

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power generation. Production of clean gas will ensure the reliability of the system, ease of operation and maintenance.

The majority of the biomass gasifier based power generation projects deployed under the rural electrification program across the country are of single stage downdraft type reactors. Generally two types of reactors are used in the downdraft gasifiers. They are either throat-less design or throated design. The tar content in the raw gas of the producer gas, generated from a downdraft gasifier, is reported as 2000 mg Nm^{-3} [9]. The tar content in the clean gas is reported as 10 to 50 mg Nm^{-3} [10, 11]. The raw gas is the gas which exits from the gasifier reactor, i.e. the gas before cleaning. Preferable tar level in the clean gas has to be closer to nil or at least less than 25 mg Nm^{-3} for running internal combustion engines.

A tow stage gasifier with a horizontal pyrolyser coupled with a vertical reactor produces the gas having the tar content as less than 15 mg Nm^{-3} [12]. This gasifiers system has an externally heated pyrolyser, which converts the fuel wood in charcoal and a char gasification reactor. The pyrolyser is mounted horizontally and connected with the char gasification reactor which was mounted vertically. A screw feeder is used in this system to transfer the pyrolysed fuel wood into the char gasification reactor. It may be noted that the reactors of stage I and stage II are placed vertically as one on top of another. This arrangement enables a free fuel flow without adding to additional components and auxiliary power consumption. The gasification reactor is provided with a single level air entry. A maximum temperature of 1100 °C, in the oxidation zone was reported with a supply of preheated air. However this paper does not report the temperature of the preheated air. The corrosion of metals in the high temperature zone and use of metallic reactors to withstand high temperature are reported in Ref. [12]. The improved system does not have direct contact with metal as the high temperature zone is lined with refractory casting.

A multi-stage gasification system for reduction of tar in raw gas was reported in [13]. The multi-stage gasifier system has an inclined screw conveyer to transfer the pyrolysed biomass fuel into the main gasification reactor. Some of the gasifier uses the two-stage gasification concept by circulating the pyrolysis gas through hot charcoal bed, which has its own limitations. A charcoal gasifier coupled two-stage gasifier system and a floating drum storage tank was used to reduce the tar content in the gas [14]. During the World War II charcoal gasifiers were used by Germans to power their automobiles and other vehicles. Charcoal gasifiers produce relatively tar free gas since the charcoal is free from volatile matters.

The present research work aims to design and develop an improved dual fired downdraft gasification reactor. Dual fired downdraft gasifier enables to produce a good quality producer gas with low tar content, which is closer to that of charcoal gasifiers. The improved dual fired gasifier system aims to reduce the dust content of the producer gas at the gasifier exit, itself (raw gas). This will reduce the dust and tar content at the source, resulting in reduction of tar and dust loading rate on the gas cleaning train.

The improved dual fired downdraft gasifier has two gasification reactors. These gasification reactors are vertically mounted as one on top of the other. Since the reactor is dual fired, the gasification of biomass occurs in two stages. In stage one, the biomass fuel is converted into producer gas and charcoal. In stage two, the gas produced on stage one is further refined and the charcoal is converted into producer gas. Since both of the reactors are mounted vertically one above the other, it ensures a smooth flow of fuel in the reactor. In this arrangement a smooth fuel flow is ensured in the reactor by gravity, instead of using a screw feeder, as in the case of the conventional two-stage gasifier.

The dual fired downdraft gasifier is designed and developed to remove the complexity of the existing two-stage gasifier system. In the proposed dual fired system, the design configurations were arrived to ensure the user friendliness in terms of operation as well as maintenance.

2. Objectives of the research work

The specific objective of this research work is to design and develop an improved dual fired downdraft gasifier system, to generate a good quality gas for power generation. One of the major objectives is to design a reactor to produce the gas with low tar content, as compared to the existing common downdraft gasifiers. It is also aimed at having a system with “ease of operation and low maintenance”. These are the critical parameters, which will enable large-scale adoption of the system in remote villages, to produce power. Wastewater treatment and disposal of the used water are the major challenges that were commonly faced in the existing designs of downdraft gasifier systems. The improved dual fired downdraft gasifier system is designed to have a dry gas cleaning system to avoid usage of water based scrubbing. The key objective of this research work is to design a biomass gasification system which can produce cleaner gas. The objective of this research work includes design and development of a dry gas cleaning system with easy in operation and maintenance.

2.1. Issues related to biomass gasification

Producing gas from biomass is not an issue but producing a good quality gas suitable to drive an internal combustion engine for power generation is a challenging task. Most of the research activities are focused on improving the gas quality either by primary measures, improving the gas quality at the source itself) or by secondary measures (improving the efficiency of the gas cleaning equipment in downstream) [15]. There are many researchers involved in two-stage or multi-stage gasification reactors [12,13,15,16]. Multi-stage gasifiers can be classified in two categories named single line and double line process [15]. The improved dual fired gasifier system employs a single line processing, in which only one main stream through two reactors (stage I and stage II) arranged vertically as one on top of another.

Producer gas engines work at a very low efficiency (at 18%) in comparison with the engines working on diesel or natural gas [17,18]. Apart from gas quality the overall power generation efficiency using biomass gasifiers needs to be improved. Low heating value of the producer gas and cold gas efficiency affects the overall power generation efficiency from biomass. To understand the status of the gasification technology, the view of the gasifier manufacturer and the users were collected [19]. There are 11 issues related to the quality of the producer gas, complexity of the technology, economic and practical viability was highlighted in this report, published 1906. Even after more than a century, some of the issues elated gasifier and producer gas engines remain unsolved or need to improve even in today’s technology status. When solving the issues related to gas quality, it is equally important to take care of the financial and practical viability of the technology. A gasifier system producing high quality gas demanding more capital investment and complex operation and maintenance will not be able to promote. The present research work is focused to improve the gasifier system, with consideration of practical and economic viability. The areas focused for improvement and the benchmark targets are listed in Table 1.

3. Methodology

Design and development of a dual fired downdraft gasifier system is aimed to produce cleaner gas and to work with high conversion efficiency of biomass into gaseous fuel. Design and

Table 1
Issues and targeted benchmark.

S. No.	Issues	Target benchmark	
		Unit	Benchmark
1	Tar content at the exit of the gasifier (primary tar reduction, from the source itself)	mg Nm^{-3}	<100
2	Tar content at the exit of the cleaning system By the gas cleaning equipment in the downstream)	mg Nm^{-3}	<50
3	Dust content at the exit of the ash pit (primary reduction, from the source itself)	mg Nm^{-3}	<200
4	Tar content at the exit of the cleaning system (By the gas cleaning equipment in the downstream)	mg Nm^{-3}	<50
5	Heating value of the gas	MJ Nm^{-3}	>5.5
6	Cold gas efficiency	Energy fraction Percentage	>85
7	Overall power generation efficiency	Energy fraction Percentage	>20

development of the improved dual fired gasifier system were carried out in two steps. The improvement in the gasifier system was aimed to achieve the benchmarks listed in Table 1. The first step is to design and develop a dual fired downdraft gasification reactor to reduce the impurities at the source, which is at the exit of the gasifier itself. Tar reduction at the source was aimed by incorporating design improvement in the dual fired gasifier reactor. It is aimed to improve the reactor performance by reducing the heat loss by multiple layers of insulation, recycling of waste heat from the hot gas through hot air injection and reducing the charcoal yield in the ash pit for complete gasification of biomass fuel. The load on gas cleaning equipment will be minimized due to reduce the impurities at the source itself. In the second step it is focused to design and develop an efficient gas cooling and cleaning train to make the producer gas suitable to run an internal combustion engine.

3.1. Design and development of dual fired fixed bed downdraft type biomass gasification reactor

Biomass is converted into producer gas in a high temperature reactor, which is an insulated chamber with a partial supply of air. A lab scale model with dual fired two-stage gasifier was reported by [2]. The gasifier reactor considered under this study has a double wall insulation layer, an improved ash removal system and has provision for hot air injection. Key design parameters, that have a larger influence on the reactor performance were identified and studied. The reactor's design parameters are optimized for obtaining cleaner gas and to ensure smooth operation of the system. Some of the design parameters and their impact on the operation of the system are listed below:

- The specific gasification rate is inversely proportional to the cross-section area of the reactor.
- Increase in gasification rate can provide high quality gas but will act as a barrier to the flow of biomass.
- Increased insulation will improve the gas quality by increasing the reactor temperature but it will add to the complexity in terms of fabrication and cost.
- High reactor temperature will increase the gas quality but add to the problem related to ash melting.
- The increased ash return rate will eliminate melting of ash but will result in to low gasification efficiency.

The key design parameters of the reactors were studied and optimized for improving the gas quality.

3.1.1. Specific gasification rate

Specific gasification rate (SGR) is defined as gas flow rate per hour over a specified unit area of the reactor. Design parameters related to specific gasification rate as hearth load is discussed in by [20,21].

'Specific gasification rate' of a reactor can be estimated by Eq. (1).

$$\mathrm{SGR} = \frac{F_{\mathrm{cr}} \times G_{\mathrm{cr}}}{A \times T} \tag{1}$$

3.1.2. Solid residence time

Solid residence time (SRT) is defined as the time taken by the solid biomass fuel to pass through the reactor. SRT of solid biomass fuel in a reactor can be estimated by Eq. (2).

$$\mathrm{SRT} = \frac{R_{\mathrm{v}} \times \rho_{\mathrm{bm}}}{F_{\mathrm{cr}}} \tag{2}$$

3.1.3. Gas residence time

Gas residence time (GRT) is defined as the time which the gas takes to pass through the reactor. GRT can be estimated by Eq. (3).

$$\mathrm{GRT} = \frac{R_{\mathrm{v}} \times V_{\mathrm{fb}}}{G_{\mathrm{fr}}} \tag{3}$$

3.1.4. Insulation layer

Insulation layer plays an important role to reduce the heat loss through the sidewall of the reactor. Insulation layer is provided to withstand high temperature up to 1600 °C. The reactor is provided with two layers of insulation. High alumina insulating refractory cast was used to insulate the reactor for minimizing the heat loss. The conductivity of the insulation materials is in the range of 8–15 W m^{-1} K^{-1} at 1400 K. The insulation layers enhance the durability of the reactor, due to its property to withstand the high temperature.

3.1.5. Rate of charcoal return

Rate of charcoal return along with ash determines the biomass to gas conversion efficiency of a reactor. The ash removal system has a larger influence on the charcoal return rate. Hence a vibrating grate ash removal system is designed. The vibrating grate ash removal system minimizes the charcoal return into the ash pit and maximizes the conversion efficiency of biomass into producer gas.

3.1.6. Reactor improvements

In stage I of the gasification reactor the fuel wood was converted into charcoal and producer gas is generated. The gas generated at this stage is similar to the quality from a single stage Imbert gasifiers. The tar content of the gas from the conventional single stage gasifier is in the range of 500–700 mg Nm^{-3} [13]. To improve the quality two-stage or multi-stage gasifiers were developed. These gasifiers produce the gas with low tar content in the range of 19–34 mg Nm^{-3} [13]. The two-stage gasifier generates the gas with a tar content of less than 25 mg Nm^{-3} [12]. The present study is focused on developing dual fired gasification reactor (with two stages) for generating a good quality gas from biomass.

Three types of reactors were developed and improved during the study. These reactors are fixed bed downdraft type with dual air supply nozzles. Tar and dust content in the gas are considered as indicators for performance assessment of these three reactors. Based on these assessments, improvements in the reactor design were carried out. Details of the components of the reactors that were modified are shown in Fig. 1. The rector I is built with single layer of insulation. The reactor II is built with two layers of

insulation in order to maintain much higher temperatures of the hot charcoal bed in the reactor. Reactors I and II were having an oscillating grate for ash removal. To reduce the charcoal return to ash pit, a vibrating grate ash removal system is introduced in reactor III. All the three types of the reactors were designed with two stages of gasification. These reactors of stage I and stage II are placed vertically as one on top of another. This arrangement enables a free fuel flow without adding to additional components and auxiliary power consumption. A screw feeder is used to transfer the pyrolysed fuel wood into the char gasification reactor [12]. The gasification reactor in Ref. [12] is provided with a single level air entry. The erosion of metals in the high temperature zone and use of metallic reactors to withstand high temperature are reported in Ref. [12]. The improved system does not have direct contact with metal as the high temperature zone is lined with refractory casting. When the stage I and stage II of the reactors were separated like [12], The gas quality of two-stage gasifier varies due to the variation in charcoal quantity in stage II [16]. To obtain a good quality gas preheated air is supplied into the reactor. The gasification efficiency is improved by recycling the waste heat into the reactor.

3.1.7. Vibrating grate ash removal system

A vibrating grate ash removal system was designed to minimize the charcoal yield into the ash pit. A vibrating grate was operated at a regular interval. It consists of an ash removal grate, an electric motor coupled with a vibrator, and a vibration transmitter. The duration of the vibration and frequency of operation of the grate can be varied depending upon the operating load of the gasifier. A timer switch has been programmed in such a way to activate the vibrator at desired intervals. This ash removal system allows only the dust particles and ash to pass through the grate and avoids falling of charcoal from the reactor. The cold gas efficiency was improved by minimizing the amount of charcoal, falling out from the reactor. A diagram of the gasifier with the details of the reactor, air heating arrangements and vibrating grate ash removal system are shown in Fig. 2. The dimensions provided in the figure are in mm.

3.1.8. Reduction of dust content of the producer gas

In reactor III, it may be noted that the gas is drawn at low velocity to drop the dust in the ash pit and moves upward from the other end of the ash pit. The upward motion of the raw gas enables separation of the particulate matter carried away by the gas. By drawing the gas at a low velocity and in the upward direction the dust content is reduced significantly.

3.2. Gas cleaning and cooling system

The gas coming out from the exit of the gasifier needs to be further cleaned before it is fed into an internal combustion engine. Hence a cleaning and cooling train is introduced into the system by connecting the equipment in series. It consists of a heat exchanger I, bag-house filter, heat exchanger II, heat exchanger III and a paper filter. The partially cleaned hot gas is passed through a shell and tube (gas to air) heat exchanger I.

3.2.1. Details of the heat exchanger

A shell and tube heat exchanger was used to preheat the air from the sensible heat of the hot producer gas. Air passes through the shell and the gas is passed through the tubes. With heat exchanger I ambient air is preheated up to 250 °C and the gas get cooled down from 375 °C to 150 °C. The overall dimension of the heat exchanger was 610 mm × 265 mm × 1200 mm ($l \times b \times h$). The heat exchanger was designed with three passes. The hot gas is drawn through the shell and the ambient air is drawn through the tube. In the heat exchanger, gas and air flow in the opposite direction. A total of 36 tubes were used in three phases of the heat exchanger. In each pass, 12 tubes were provided in 4 rows and 3 columns. The dimensions of the tubes are, inner diameter as 38 mm and outer diameter as 42 mm. The total length of the tube was 39.2 m. The tubes were placed at a distance of 60 mm, from center to center.

The hot gas at 150 °C is passed through the bag-house filter where the particulate matter is removed. The gas temperature is maintained above 120 °C in order to avoid any condensation inside the filter. Any condensation of moisture from the gas can result in clogging of the bag-house filters used to remove the dust. Clogging of the bag-house filter can increase the pressure drop and will reduce the gas flow rate. Thus the gas is cleaned before cooling it to ambient temperature.

Gas cooling is achieved by using shell and tube heat exchangers in three stages. During the first stage in the heat exchanger I, air is passed through the shell and hot gas is passed through the tubes. In the process of cooling the gas, the primary air supplied for pyrolysis and gasification is preheated. Heat exchanger II is located after dust filter to cool the hot gas further before supplied to the engine. In the heat exchanger III the gas is further cooled down, closer to the ambient temperature. Here the gas is passed through the tubes and the cold water is passed through the shell. An evaporative cooler is provided to reject the heat gained from the gas. A mist separator is introduced at the exit of the heat exchanger III to trap the mist

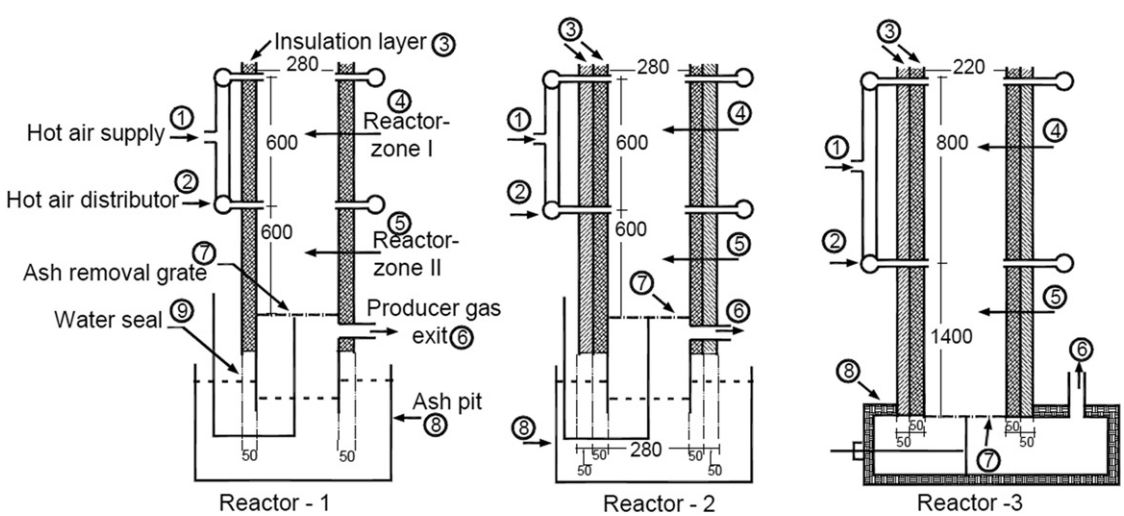

Fig. 1. Details of the reactors along with its components.

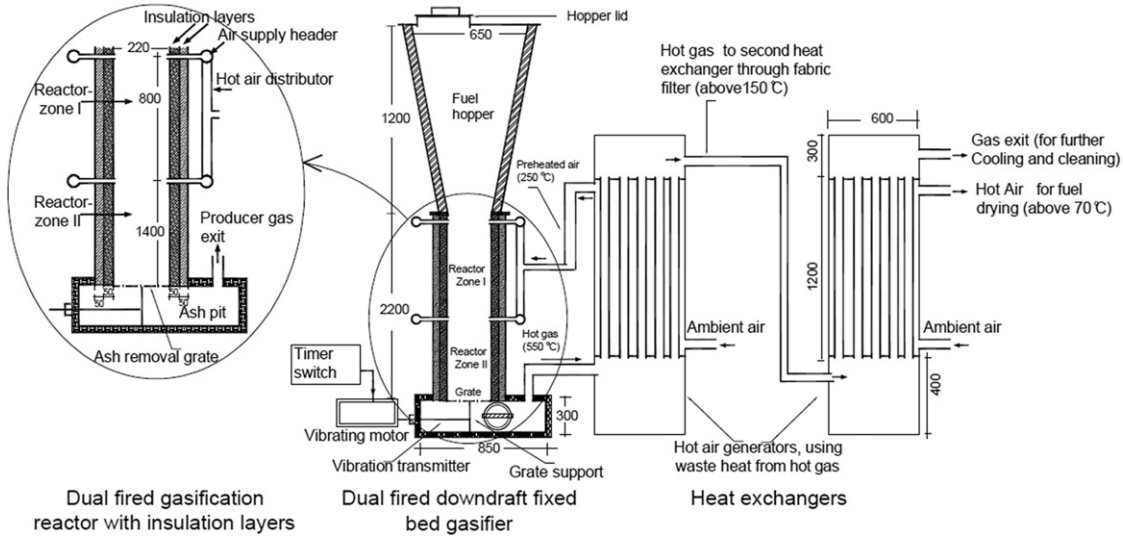

Fig. 2. The details the gasifier, ash removal system and the air heating arrangement.

formed due to cooling of the gas. After the mist separator a paper filter cartridge is used as a safety filter to ensure removal of particulate matter before the gas is supplied to the engine. In between the paper filter and the engine, a gas air mixture is introduced to provide a proper fuel mixture to the engine.

The gasifier is operated with a blower at force draft mode. A suction blower is introduced between the second and third heat exchanger to compensate the pressure drop created across the system.

A conceptual diagram of the dual fired gasifier system along with the details of gas cleaning and cooling components is shown in Fig. 3.

3.3. Reactor performance, study and analysis

The performance of the gasifier reactors is analyzed by estimation of the tar and dust content of the producer gas, at the exit of the gasifier. The solvent method is used to estimate the tar content in the gas, as per the protocol [20]. The dust content is estimated by passing a measured quantity of gas through the thimble kept at 350 °C. The difference in the initial and final weight of the thimble gives the exact quantity of dust present in the gas.

Samples of charcoal were drawn at the end of the reactor, stage I. The charcoal samples were analyzed for evaluating the performance of the gasification reactor, with respect to the reduction of volatile matter of the biomass fuel. The following parameters were considered to analyze the performance of the dual fired gasifier system.

I. Parameters considered for analysis of the fuel wood:
   a. Moisture content
   b. Volatile matter
   c. Carbon content
   d. Ash content
II. Parameters considered for the charcoal analysis:
   a. Volatile matter
   b. Carbon content
   c. Ash content in
III. Parameters considered in the estimation of cold gas efficiency:
   a. The weight of fuel wood consumed

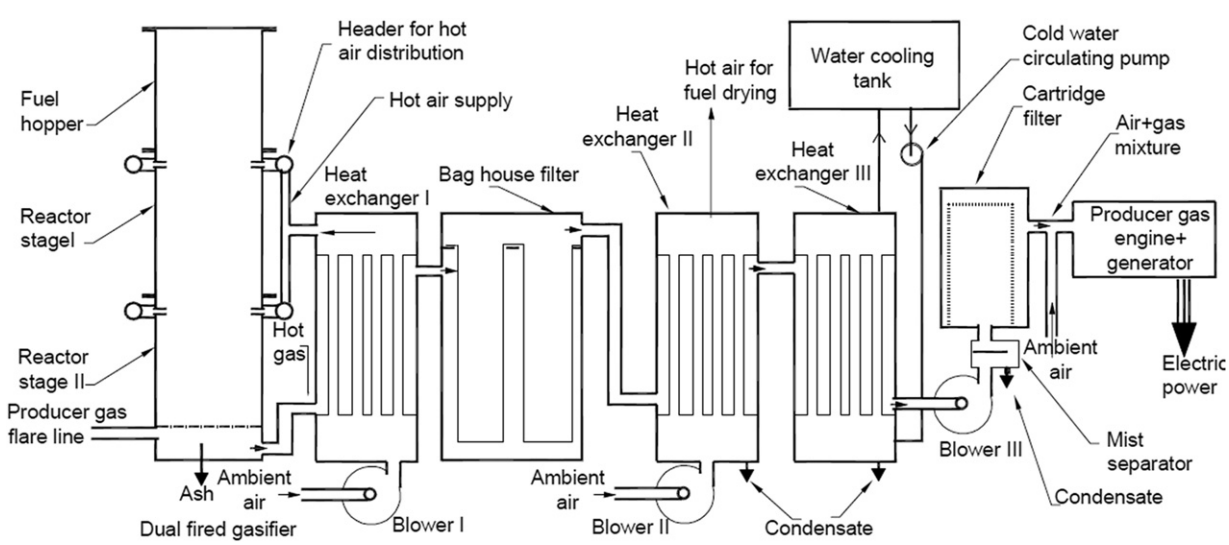

Fig. 3. Block diagram representing the components in the dual fired gasification system.

b. Heat content of the fuel wood
c. Moisture content of the fuel wood
d. Components of the producer gas and energy content

3.3.1. Estimation of cold gas efficiency

Cold gas efficiency is estimated by using Eq. (4)

$$\eta_{cg} = \frac{Q_g \times C_{fg} \times 100}{W_f \times M_c \times C_f} \quad (4)$$

3.4. Equipment and methods used for data collection and analysis

Equipment and methods adopted for data collection and analysis are listed below:

- Fuel wood is weighed using weighing balance having a least count of 0.1 kg.
- The calorific value of the fuel wood is analyzed using bomb calorimeter.
- The moisture content of the fuel wood was analyzed using the hot air oven and digital balance.
- The gas and air flow rate were monitored by using a hot wire anemometer.
- Gas components of the producer gas are analyzed using a gas chromatograph.
- The calorific value of the producer gas is estimated from the quantity of combustible gas present in the producer gas.

The details of the various equipment used during the experiment is presented in Table 2.

4. Results and discussions

4.1. Performance of the reactors

The design of the reactor and the ash removal system has a major influence on the tar and dust content in the gas. Five key performance indicators are used as a tool to study the performance of the reactors. The gas quality of three reactors, with different design configurations, was compared by estimation of the tar and dust content of the producer gas. The tar and dust content were estimated in the producer gas sampled at the exit of the gasifier and at the exit of the gas cleaning system. A profile showing the tar content of the gas at the exit of the gasifier and clean gas is presented in Fig. 4. Here, the clean gas refers to the gas which exits the final filter of the gas cleaning train, as shown in Fig. 3. A profile showing the dust content of the gas at the exit of the gasifier and clean gas is presented in Fig. 5. The design parameters and the performance indicators of all the three reactors are presented in Table 3. The tar content and dust content provided in Table 3 are the average of the test results provided in Figs. 4 and 5.

Table 2
The details of the various equipment used during the experiment.

S. No.	Instrument	Measurement	Least count	Error level
1	Hot wire anemometer	Flow measurement	0.1 m/s	±1%
2	Pressure differential meter (PDM)	Pleasure drop	0.1 mm	±0.2%
3	Digital temperature indicator	Temperature measurements	0.1 °C	±1%
4	Weighing balance	Fuel feeding rate	100 g	±20 g
5	Watt meter	Monitoring the power output	1 Wat	±0.5%
6	Energy meter	Monitoring the energy output	1 kWh	±0.5%
7	Gas chromatograph	Gas component analysis	0.01%	±1%

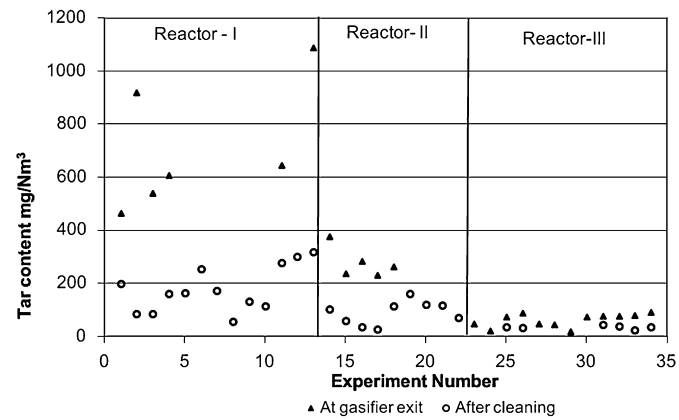

Fig. 4. Tar content of the producer gas at the exit of the gasifier and after cleaning train.

4.1.1. Improvement in the performance of the reactor III

The tar content in the gas at the gasifier exit was brought down from 711 mg Nm^{-3} to 67 mg Nm^{-3}, using the reactor III. The dust content of the gas at the gasifier exit was brought down from 1360 mg Nm^{-3} to 53 mg Nm^{-3}. The tar content of the gas at the exit of the gas cleaning system was brought down from 178 mg Nm^{-3} to 35 mg Nm^{-3}. The dust content of the gas at the exit of the gas cleaning system was brought down from 3.2 mg Nm^{-3} to nil. It may be noted that the ash and charcoal return in the ash pit was brought down from 8% to 1%. By recycling the waste heat into the reactor and by minimizing the charcoal return to ash pit, the cold gas efficiency was increased from 72.9% to 89.7%. A maximum cold gas efficiency of 64.3% was reported, when the heating value of the gas was at 5.38 MJ Nm^{-3} [22]. Hence, the design configuration of reactor III is considered to be the best to produce good quality gas, which is suitable for operating the internal combustion engines.

4.1.2. Temperature profile across the reactor III

The temperature profile across the reactor III, at the level of the air supply nozzles, is shown in Fig. 6. The reactor temperature is one of the key factors that have an influence on producing cleaner gas. A maximum of 900 °C was achieved, with secondary air supply in the oxidation zone of a double air supply downdraft gasifier [21]. A maximum temperature of 1100 °C was obtained in the present dual fired with the secondary air supply. In comparison with [21], an

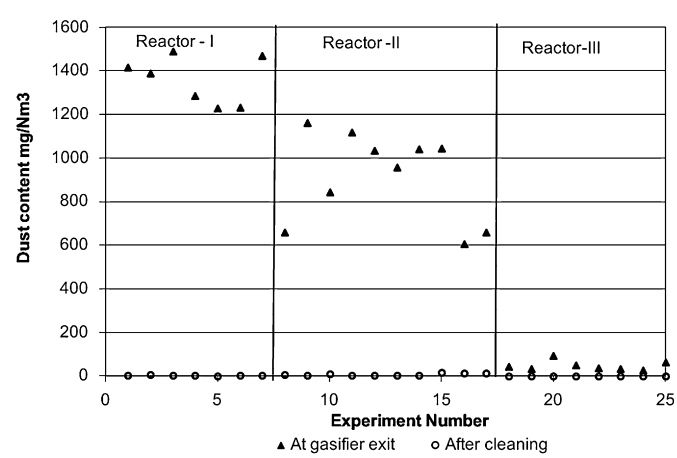

Fig. 5. Dust content of the producer gas at the exit of the gasifier and after cleaning train.

Table 3
Design parameters and performance indicators of the gasification rectors.

	Reactor – I	Reactor – II	Reactor – III
Design parameters			
Specific gasification rate ($Nm^3\,cm^{-2}\,h^{-1}$)	0.1	0.1	0.2
Gas residence time, in each of the gasification zone (s)	0.6	0.6	1.0
Solid residence time, in each of the gasification zone (min)	27	27	44
Insulation layer (in number)	One	One	Two
Ash removal system	Oscillating grate	Vibrating grate	Vibrating grate
Performance indicators			
Gas temperature at the exit of gasifier	260	350	550
Hot air temperature at the exit of heat exchanger (in °C)	160	200	250
Tar content at the exit of the gasifier ($mg\,Nm^{-3}$)	711	278	67
Tar content in clean gas ($mg\,Nm^{-3}$)	178	90	35
Dust content at the exit of the gasifier ($mg\,Nm^{-3}$)	1359.7	913.1	53.2
Dust content in clean gas ($mg\,Nm^{-3}$)	3.2	7.1	Nil[a]
Ash and charcoal return in ash pit (% by mass of input)	8	5	1
Cold gas efficiency (% by energy input)	72.9	82.0	89.7
Specific fuel consumption ($kg\,kWh^{-1}$)	1.5	1.5	1.1

[a] Measurable quantity of dust was not captured while using 0.8 μm thimble filter.

increase of 200 °C was observed in the oxidation zone due to hot air supply and the insulation of the reactor. The gas quality of the dual fired gasifier was increased by achieving a maximum temperature and maintaining it at large portion of the reactor (as shown in Fig. 6). Multilayer insulation enables a uniform distribution of the high temperature zone.

It may be noted that a minimum temperature of 935 °C was observed near the reactor wall. Higher temperature was observed near the inner wall of the reactor due to hot air supply and double layer insulation. Across the top nozzle, the charcoal bed temperature rises gradually from 935 °C to 1100 °C at 10 cm away from the reactor wall. Across the bottom nozzle, the charcoal bed temperature rises gradually from 935 °C to 1050 °C at 5 cm away from the reactor wall. It may be noted that, across the bottom nozzle, a large area is above 1000 °C when compared to the temperature profile across the top nozzle. This is due to the fact that across the top nozzle (stage I) volatile gas and fuel wood are burnt and across the bottom nozzle (stage II) gas and charcoal are burnt. High reactor temperature and increased gas residence time enhance the effectiveness of tar cracking inside the reactor. Hence the production of good quality gas with low tar content is made possible with reactor III.

4.2. Performance of the heat exchanger

The gas temperature was measured at the exit points as shown in Fig. 3. Reactors I and II are provided with a water seal at the ash pit and reactor III was designed without a water seal. In reactor III the hot gas temperature at the exit was 550 °C and the temperature was dropped down to 375 °C when it reaches the inlet of the heat exchanger I. The temperature dropped due to the heat loss at the pipeline carrying the producer gas and at the surface of the ash pit.

The producer gas temperature at the exit of the gasifier was 550 °C. In the conventional gas scrubbing systems, the sensible heat available from the hot gas is wasted in the cooling process. In the proposed dual fired gasifier system the sensible heat energy from the hot gas is used to pre-heat the ambient air supplied to the gasifier. By

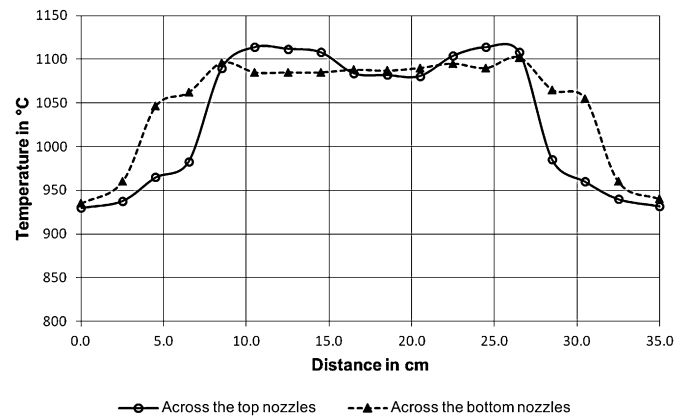

Fig. 6. Temperature profile across the nozzles in reactor III.

recovering the sensible heat of the hot gas, the ambient air is preheated from 26 °C to 250 °C. Hot air supply enables to achieve a high temperature in the gasification reactor. High reactor temperature enhances better tar cracking and to produce good quality gas.

The gas temperature at the gas outlet of the heat exchanger-I was brought down to 123 °C. The performance of the heat exchanger-I is analyzed by measuring four temperatures at four locations. They are gas inlet, gas outlet, air inlet and air outlet of the heat exchanger. Time versus temperature at various locations of the heat exchanger I is presented in Table 4.

Heat exchanger II was designed to cool the gas by using ambient air. At heat exchanger II, the gas temperature is brought down to 70 °C. The hot air generated at this stage is above 60 °C, which was used for drying the fuel wood. At heat exchanger III, the producer gas is cooled indirectly using cold water. Here the gas is cooled without having direct contact with water unlike in the case of wet scrubbers. Thus, the improved dual fired gasifier system doesn't produce any polluted water. At the exit of heat exchanger III, the gas is brought down to 35 °C, which is closer to ambient temperature.

4.3. Performance of the stage I and stage II of the gasification reactor

4.3.1. Reactor stage I

The gas produced at the end of gasification reactor stage I is similar to the gas quality from a throat-less downdraft type, with single stage reactor. Since the gas produced from the single stage

Table 4
Temperature across the heat exchanger.

Time (hours)	Gas interactions in the heat exchanger		Air interactions in the heat exchanger	
	Inlet (°C)	Outlet (°C)	Inlet (°C)	Outlet (°C)
0	345	105	23	187
1	371	122	23	205
2	361	122	23	185
3	378	130	26	231
4	360	114	27	225
5	369	182	26	245
6	353	123	27	215
7	373	122	26	251
8	380	122	26	225
9	372	115	25	250
10	359	156	23	247
11	365	107	22	224
12	361	103	22	206

gasifiers have more tar content, there is a need to reduce the tar content to further to use it in internal combustion engine (ICE). About 70% of the air required for gasification is supplied for gasification at stage I by maintaining high temperature above 950 °C and with a partial combustion the charcoal leaving the stage one of the reactor has very less volatile matters and high carbon content. Eventually the stage II of the reactor was ensured with a free flow of good quality charcoal for gasification. In stage I the biomass is partially burnt and converted into charcoal.

The stage I of the gasifier reactor was designed to reduce the volatile matter present in the fuel wood. It also plays a key role to ensure the complete conversion of wood into charcoal before the fuel enters into the stage II of the reactor. The quality of the commercially available charcoal is considered as a benchmark to assess the quality of charcoal produced by stage I of the gasification reactor. Various components are studied for comparisons of the quality of the charcoal produced in stage I. They are moisture content, volatile matter, fixed carbon and ash content. These components for commercial charcoal, charcoal from pyrolyser and fuel wood was obtained by getting the samples analyzed by an accredited laboratory. The results obtained by analyzing the charcoal samples, collected at the end of the stage I of the dual fired reactor was compared with commercial quality charcoal. The result of the analysis is presented in Table 5. A comparison of the volatile matter, fixed carbon and ash content of the charcoal produced after stage I of the gasification reactor is given in Fig. 7. The volatile matter of the fuel wood is reduced from 76.75% to 27.77%. It may be noted in Fig 7. The commercial charcoal was having 35.88% of the volatile matter. The stage I of the reactor was producing the charcoal with 27.77% of volatile matter, which is 30% less than the commercially available charcoal. The carbon content of the charcoal produced from the pyrolyser was 15% higher than the carbon content of the commercial grade charcoal. The stage I of the reactor produce a high quality charcoal with 64% reduction of the volatile matter from the feed material. Efficient reduction of the volatile matters of the fuel wood and production of high quality charcoal from the stage I of the reactor, contributes to reduction of tar content in the producer gas.

4.3.2. Reactor stage II

In stage II of the reactor about 30% of the air required for gasification of biomass was supplied with four nozzles located at the same level. All the four nozzles are located at an equal distance to have a uniform temperature across the reactor. In stage II the gas produced in stage one is partially burnt and the tar cracking process is further enhanced at a high temperature charcoal bed (charcoal with high carbon content. In the present system the stage I of the reactor vertically mounted on top of the reactor stage II. The charcoal flow to stage II of the reactor is by gravity itself, without using any screw conveyer system. In stage I, the producer was generated with the charcoal, which was still in the process of conversion into carbon. The reactor of stage I was designed in such a way that the charcoal leaving the stage I will have the carbon content more than 85%. Stage II of the reactor produces the gas with low tar content, since the gas produced in stage one is passed through high quality and a high temperature charcoal bed. The preheated air supplied increases the bed temperature.

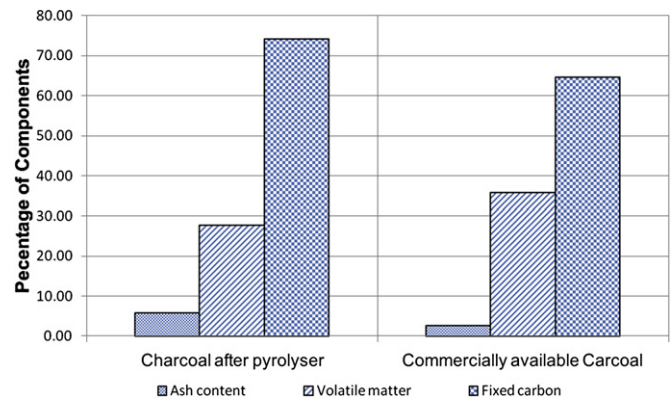

Fig. 7. Comparison of the charcoal produced from the pyrolyser zone with the charcoal procured from the market.

4.4. Performance of the gasification reactor III

The objective of the design and development of a dual fired gasification reactor is to reduce the tar content in the raw gas itself as less than 100 mg Nm^{-3}. In regular operation of the system the tar content in the gas produced by a reactor III, is less than 100 mg Nm^{-3}. The tar and dust content in the producer gas at the exit of the gasifier is presented in Table 6. From Table 6, it may be noted that the tar content in the producer gas is varied from 18 mg Nm^{-3} to 90 mg Nm^{-3}. Also, from Table 6, it may be noted that the dust content in raw gas varies from 25 mg Nm^{-3} to 100 mg Nm^{-3}.

A modified two-stage gasifier coupled with a charcoal gasifier produces the gas with 19–34 mg Nm^{-3} [13]. A tow stage gasifier (with steam injection) produces the gas having the tar content as less than 15 mg Nm^{-3} [12]. The present dual fired gasifier system is producing the clean gas less than 50 mg Nm^{-3} of tar content and zero dust level (measured using 8 μm filter). The importance of the gas quality for power generation using IC engines and gas turbines were reported in detail by Ref. [23]. This paper suggests, externally fired gas turbine (EFGT) for power generation due to the impurities in the gas. Since the impurity of the gas produced from the present

Table 5
Details of charcoal analysis.

Sample details		Ash content in %	Volatile mater in %	Fixed carbon in %
Fuel wood	Sample 1	2.03	73.32	24.65
	Sample 2	1.48	80.19	18.33
	Average	1.76	76.75	21.49
Charcoal after pyrolysis zone	Sample 1	5.88	28.54	73.45
	Sample 2	5.81	27.00	74.89
	Average	5.84	27.77	74.17
Commercially available charcoal	Sample 1	2.86	36.13	63.90
	Sample 2	2.30	35.64	65.38
	Average	2.58	35.88	64.64

Table 6
Tar and dust content of the producer gas at the exit of the gasifier using the reactor III.

Experiment number	TAR (mg Nm^{-3})	Dust (mg Nm^{-3})
1	48.68	44.97
2	21.66	31.93
3	74.86	94.98
4	89.50	51.12
5	47.64	37.16
6	43.54	34.14
7	17.17	25.35
8	73.79	64.88
9	75.23	53.43
10	77.29	46.08
11	79.35	69.59
12	90.33	84.76

dual fired gasifier system is very low with zero dust content, it can be directly used in the gas turbines, with internal firing.

4.5. Performance of the dry gas filter

Spray tower and mist separator with wire mesh were used to cool and clean the gas [21]. The present system was designed with dry gas cleaning and indirect cooling method using heat exchangers. Spray towers and mist eliminators using wire mesh are completely eliminated. The water spray cooling system has an additional task of water treatment and disposal. Also using water spray increases the moisture content of the gas and reduces its heating value. The dual fired system presented in this paper has a dry gas cleaning system, without using water spray.

The dry gas filter was operated in the temperature range of 120–150 °C, to avoid any condensation. The pressure drop across the dry gas filter was 25 cm of WG at 13 kW_e load. The pressure drop across the bag-house filter was on the order of 250 cm in the earlier single throated design. In the present dry gas cleaning system the maximum pressure drop across the bag-house filter is only 25 cm of water gauge (WG). This is about a 10 times reduction in the pressure drop, compared with the earlier gasifier systems (having the reactor types I and II). The low pressure drop is achieved due to the cleanliness of the raw gas and dry gas filtration method. Reduction of pressure drop across the bag-house filter also reduces the maintenance cycle to seven times. Reduction in maintenance cycle increases the ease of operation. After the dry gas filter, no measurable dust particulate was captured in the thimble (of 8 μm). This indicates a zero dust level in the clean gas is achieved through dry gas filtration.

4.6. Components of the producer gas from dual fired gasification system

The gas components of the producer gas from the improved dual fired gasifier system were analyzed using a 'Gas chromatograph (GC)'. The mass fraction of the moisture content of the raw gas was estimated as 4.8%. The moisture of the gas is condensed and drained from the heat exchangers installed for cooling the gas. About 4–5 l of water is removed at an interval of every two hours, when the fuel consumption was at 15–17 kg h^{-1}. At the exit of the gas cooling and cleaning train the mass fraction of the moisture in the producer gas was 1.4%.

On dry basis, producer gas from the improved dual fired gasifier system contains 10.7% of CO_2, 20.5% of CO, 21.3% of H_2, 1.1% of methane and nitrogen as 46.4% (by balance). A 9% of CO_2, CO and H_2 as 18% from an open top downdraft gasifier are reported by Ref. [18]. With these components, the calorific value of the gas works out to be 4.8 MJ Nm^{-3}. About 20% of CO_2, 17% of CO and 33% of H_2 from a two-stage gasifier is reported by Ref. [12]. This gasifier produces the gas with higher hydrogen content due to steam gasification. The calorific value of the gas with increased Hydrogen content works out to be 6.1 MJ Nm^{-3}. Various components of the gas obtained from the improved dual fired gasifier system are given in Table 7. The gas components of the producer gas reported in Table 7 is on dry basis. Based on the gas component, the calorific value of the gas is worked out to be 5.3 MJ Nm^{-3}. This is 10.4% higher than the normal downdraft gasifier systems. A gasifier operated with hazelnut shell produce the gas with a calorific value of 5 MJ Nm^{-3} at an ER of 0.27 [24]. The heating value of the gas produced by this system is 6% lower than the dual fired gasifier. With double air gasification, an average heating value of 4.7 MJ Nm^{-3} was reported in [21]. The heating value of the gas generated by the present dual fired system is 13% higher than the reported value in Ref. [21].

Table 7
Composition of the producer gas from the improved dual fired gasification system.

Component	Volume fraction % db
Co_2	10.7
Co	20.5
CH_4	1.1
H_2	21.3
N_2	46.4

4.7. Analysis of equivalence ratio

Equivalence ratio is one of the important parameters which influence the gasification efficiency. Equivalence ratio (ER) is defined by the ratio between the air supplied for gasification and the air required for complete combustion. The input material to the gasifier consists of 98 kg of fuel wood and 178 kg of air, which is converted into 271 kg of producer gas. Using these values it is estimated that 1.8 kg of air is used for gasification of 1 kg of fuel wood. This corresponds to an ER of 0.29. This is 17% less than the ER reported by Ref. [25]. In the mass and energy balance analysis reported by Ref. [26] the ER is in the range of 0.21–0.29. A two-tier air supply downdraft reactor is studied by Ref. [27], this study reports at ER of 0.4, the calorific value of the gas is 4.3 MJ Nm^{-3}. With an ER of 0.27 a hazlenut fired gasifier produces the gas with 5 MJ Nm^{-3} [24]. The improved dual fired gasifier system with an ER of 0.29 produces the gas with 5.3 MJ Nm^{-3}. The heating value of the producer gas generated from a reactor with an ER of 0.4 was 5.15 MJ Nm^{-3} [21].

4.8. Charcoal return rate and biomass to gas conversion efficiency

The output products of biomass gasification consist of producer gas, ash and fine particulates. 97.7% of the biomass fuel fed to the gasifier is converted into producer gas. Biomass to gas conversion efficiency of 92.3% are reported by Ref. [18]. Biomass to gas conversation efficiency of dual fired gasifier is increased by 5.4% when compared with Ref. [18]. A 3.5% of charcoal and ash returnis reported by Ref. [28] and 3–4% is reported by Ref. [26]. In the dual fired gasifier system the charcoal ash return into the ash pit was reduced to 1%.

4.9. Cold gas efficiency

The calorific value of the gas produced from the improved dual fired downdraft system is 5.3 MJ Nm^{-3}. The gas production rate is 2.78 Nm^3 kg^{-1}, of biomass fed to the system. With these values the gas conversion efficiency of the system works out to be 89.7%.

The cold gas efficiency was estimated based on the calorific value of the gas (5.3 MJ kg^{-1}) and the gas production rate, which is 2.78 Nm^3 kg^{-1}. The calorific value of the fuel wood was 17.6 MJ kg^{-1} on dry basis. With a 7% of moisture content the calorific value of fuel wood used for gasification was 16.4 MJ kg^{-1}. With these values 89.7% of the total energy content of the fuel wood is converted into producer gas, using the dual fired gasifier. This is much higher than the value of $69 \pm 6\%$ as reported by Refs. [14,25,27,29]. In comparison with the reported values, the biomass to gas conversion efficiency of the dual fired system is increased by 14.7%. From the cold gas efficiency it may be concluded that the total energy lost in the process of converting the biomass into producer gas is 10.3%. This is much less than the total heat loss of 20% reported in Refs. [8,14] and 30% reported in Ref. [27].

Increase in biomass to gas conversion efficiency (cold gas efficiency) is achieved by having:

i) Optimized equivalence ratio of air supply
ii) Hot air injection into the reactor and waste heat recycling
iii) Complete conversion of charcoal into producer gas through vibrating grate ash removal system. At least 3 kg of biomass is needed to produce 1 kg of charcoal. Based on this fact it is clear, that every percentage of reduction in charcoal returning to ash pit will result in a 3% increase in gasification efficiency.
iv) Increased energy content of producer gas as 5.3 MJ Nm^{-3} against 4.8 MJ Nm^{-3} (an increase of 10.7%)
v) Efficient gasification reactor with minimum heat loss through double layers of insulation

4.10. Specific fuel consumption

The improved dual fired gasifier system was used to operate an internal combustion engine. A diesel engine with two cylinders (Kirloskar make; Model: RV2) was modified to operate with 100% producer gas. The modifications include the introduction of a spark ignition system with provision for varying the timing of ignition. The engine was operated with a compression ratio of 12:1. A three phase alternator (Make: Crompton greaves) with a capacity of 15 kVA was coupled with the producer gas engine for power generation. The alternator was designed to have a power factor of 0.8. With these details, the capacity of the producer gas power generation system works out to be 12 kW_e. The details of the engine configuration are presented in Table 8.

The improved dual fired gasifier system was used to operate an internal combustion engine, which was coupled with a 15 kW_e electric power generator. The specific fuel consumption (SFC) for generation of electricity is obtained as 1.1 kg kWh^{-1}. A specific fuel consumption rate of 1.2 kg kWh^{-1} is reported by Ref. [17] and specific fuel consumption rate of 1.36 kg kWh^{-1} is reported by Refs. [14,30]. When comparing with these references the improved dual fired gasifier system has 20% of the improvement in SFC. This improvement is achieved due to reduction charcoal and ash return rate. The improved dual fired gasifier system's charcoal and ash return rate return rate is 0.7%. Ash return rate of less than 1% is reported by Ref. [17] and 3.5% of ash return is reported by Ref. [30].

During the 90 s the gasifier system was used to for power generation using dual fuel engines. At 59% diesel replacement the overall efficiency of the system was at 19% [31]. A gasifier based power generation system with 100% producer gas was installed during 2004 [32]. Fuel wood to power production efficiency of the improved dual fired gasifier system works out to be 21%. An overall electric generation efficiency of 15.9% was reported with a double stage downdraft approach [21]. In the present system the overall efficiency of power generation was increased through reduction of charcoal yield in the ash pit, recycling the waste heat from the hot gas and by reduction of heat loss from the reactor through multilayer insulation.

4.11. Environmental aspects

Low tar content in raw gas produced by the improved dual fired gasifier system enables to adopt the dry gas cleaning system. The dry gas cleaning system eliminates the wet scrubbers and reduces the problem related to water supply and disposal of polluted water. Norms and treatment level of various components of the effluent from the gas scrubber is discussed by Ref. [30]. This research paper also discusses about the treated level of the effluent from the gas scrubber, before disposal. Even after treatment, the pollutant level of few components was remaining above the permissible limit of the norms [30]. By adoption of the dry gas cleaning concept, the problems associated with gas scrubbing and disposal of wastewater are eliminated.

Table 8
Details of the engine configurations.

S. No.	Component	Unit	Details
1	Rated engine capacity (engine model: RV2)	hp	18.7
2	Rated engine speed	RPM	1500
3	Number of cylinders	No.	2
4	Dimensions ($l \times b \times h$)	mm	$1600 \times 700 \times 1250$
5	Approximate weight	kg	800
6	Bore × Stroke	mm	100 x 110
7	Compression Ratio (After modification)	Proportion	12:1
8	Type of cooling	–	Water cooling
9	Ignition system (spark ignition with advance/retard facility)	–	Cam shaft and contact breaker
10	Ignition timing	Degree	28 BTDC
11	Rated power output (Genset model: KG15WS1)	kWe	12

4.12. Comparison of the performance of the dual fired gasification system

Five different downdraft gasifier systems were compared based on their features and performance. A detailed comparison of performance of these gasifiers is presented in Table 9. The parameters selected for comparison are; type of the pyrolyser, type of the reactor, the quality of the raw gas, the technology used for the gas cleaning and cooling. The gas quality is compared based on its calorific value and tar content in the raw gas. Highest calorific value of 6.5 MJ Nm^{-3} is reported by [30] with production of high H_2 content in the gas, by adding steam. Lowest calorific value of 4.3 MJ Nm^{-3} of the gas is reported by Ref. [16]. Among the gasifiers compared, highest tar content of 750 mg Nm^{-3} is reported in Ref. [17]. The lowest tar content in raw gas 25 mg Nm^{-3} is reported by Ref. [12]. This gasifier is having an externally heated pyrolyser with a screw feeder. The screw feeder works in presence of tar laden pyrolyser gas, which may add complications in operation. The tar content in raw gas varies from 25 to 750 mg Nm^{-3}.

The improved dual fired gasifier system has the reactor of stage I, which is vertically mounted above the reactor of stage II. This eliminates the use of feeder screw, which works in a high temperature and a tar laden environment. The dual fired gasifier system simplifies the operation and maintenance issues as in Ref. [30]. The tar content of the dual fired gasifier is 37 mg Nm^{-3} higher than Ref. [12] and 10 times lower when compared to Ref. [27]. Tar content in raw gas is not available for Refs. [16,33]. Inclined screw conveyer for transferring high temperature charcoal into the reactor is used by Refs. [17,16]. The improved dual fired gasifier system produces the gas with low tar content of 62mg Nm^{-3} in raw gas. The calorific value of the producer gas is 5.3 MJ Nm^{-3}.

4.13. Mass balance and energy balance analysis

Mass balance and energy balance analysis was carried out to evaluate the performance of the dual fired improved downdraft gasifier system. According to the mass balance analysis, the biomass to gas conversion efficiency of the improved system was found to be 97.8%. According to the energy balance analysis, 89.7% of the energy from the fuel wood was converted into the energy in producer gas. The increase in efficiency was achieved due to

Table 9
Comparison of the performance with different gasification technologies.

Type of gasifier	Technical details	Gas quality	Capacity range	Year	Efficiency/SFC
A dual fired downdraft gasifier system (present system)	Preheated air for pyrolyser and gasification reactor Vertically integrated pyrolyser Hot gas cleaning Indirect gas cooling	1175 kcal Nm^{-3} Tar in raw gas: 20–100 mg Nm^{-3}	10–125 kW_e	2010	21.0% 1.1 kg kWh^{-1}
Open top re-burn DDG [30]	Multiple level of air entry Throat-less design Wet Scrubbers for gas cleaning	1275 kcal Nm^{-3} Tar in raw gas: 50–250 mg Nm^{-3}	Multiplies of 250 kW_e	1997	17.7.% 1.2 kg kWh^{-1}
Two-stage gasifier [12]	Two stage design Fully automated Dry gas cleaning system	1548 kcal Nm^{-3} Tar <25 mg Nm^{-3} in raw gas	0.2–2 MW_e	2002	25–37%
Multi-staged fixed bed downdraft gasifier [16]	Floating bed reduction reactor Pressure drop across bed	1018 kcal Nm^{-3} Tar <10 mg Nm^{-3}	250 kW_e	2006	1.0 kg kWh^{-1}
Multi-stage NO TAR downdraft gasifier [33]	Scrubbers Wet cleaning Solvent circuit	Tar <50 mg Nm^{-3}	300 kW_e	2001	Electrical: 25% CHP: 75%
Bio Max 15 [37]	Dry gas clean up Skid mounted	1288 kcal Nm^{-3}	5–100 kW_e	2004	Electrical: 15–18% CHP 75%

improved ash removal system and waste heat recycling. The results obtained during the mass balance and energy balance analysis is presented in Table 10.

4.14. A comparative analysis of the dual fired downdraft gasifier with rotary kiln pyrolysis gasification

At 450 °C, 67% of biomass is converted into a combustible gas, using an externally heated rotary kiln [34]. In addition to pyrolysis gas, this type of reactors produce char and tar. The fuel obtained from rotary kiln reactors can be used for direct combustion in furnaces. The pyrolyser gas, produced at lower temperature will have higher impurities. An additional gas treatment system is needed to convert the pyrolysis gas suitable to operate internal combustion engines (ICE) or gas turbines (GT).

Higher heating value of 10.1 MJ Nm^{-3} was obtained by a rotary kiln pyrolysis gasifier, due high hydrogen content (34.8%) and methane (8.5%) [35]. Decomposition of methane is quoted as above 750 °C of the reactor temperature. The dual fired gasifier operates at 1100 °C and has methane content as 1%. In rotary kiln pyrolysis gasifiers 32–67% of the biomass is converted into pyrolysis gas, whereas in the dual fired gasifier more than 98% of the biomass is converted into producer gas.

With an integrated pyrolysis regenerated plant, fuel wood is converted into 32% of syngas, 30% of char, 38% of tar and water [36]. This paper emphasizes on the required gas quality to operate gas turbine or IC engines, as the tar content should be less than 100 mg Nm^{-3} and the dust content less than 50 mg Nm^{-3}. This paper reports, the best range of biomass to power generation efficiency is 15–20% [36]. In the dual fired gasifier system, 98.5% of biomass is converted into producer gas. Producer gas to the power generation efficiency of the improved system is 28%. The clean gas obtained from the dual fired system is having the tar content less than 50 mg Nm^{-3} and zero dust, which satisfies the required gas quality to run GT and ICE, as reported in Ref. [36].

Table 10
Results of mass balance and energy balance analysis.

Mass balance					
Input			Output		
Component	Unit, kg	Mass fraction, %	Component	Unit, kg	Mass fraction, %
Fuel wood	98.0	35.4	Producer gas	270.7	97.8
Air	178.8	64.6	Ash	1.2	0.4
			Unaccounted	4.9	1.8
Total	276.8	100.0	Total	276.8	100.0
Energy balance					
Input			Output		
Component	Unit, MJ	Energy fraction, %	Component	Unit, MJ	Energy fraction, %
Fuel wood	1608.1	100.0	Producer gas	1442.5	89.7
			Heat loss (in pipeline before heat exchanger)	24.7	1.5
			Heat loss (in cooling process)	35.4	2.2
			Unaccounted heat loss (from reactor and ash pit)	105.5	6.6
Total	1608.1	100.0	Total	1608.1	100.0

4.15. Ease of operation and maintenance

Reduction of the impurities in raw gas increases the reliability of the system, by reducing the maintenance cycle. Reduction of the maintenance cycle will result in a reduction in the operating cost. When the maintenance of the system is improved it also improves the reliability of the system. A comparison of the maintenance schedule of the gas cleaning equipment is presented in Table 11. From the Table 11 it may be noted that the maintenance cycle of reactor III is reduced by a factor of 5–8 in comparison to reactor I. Wet scrubbers used for gas cleaning are completely eliminated by using reactor III.

Table 11
Comparison of the operation and maintenance schedule.

Maintenance operation		Period of intervention		Reduction factor
Position	Description	Reactor I	Reactor III	
Cyclone filter	Cyclone cleaning – removal of carbon deposits in the interiors	Daily	Weekly	7
Venturi scrubber	Cleaning and water changing	Weekly	Eliminated	–
Fabric filter	Removal and Washing	30 h	200 h	7
Paper filter	Cleaning and drying	25 h	300 h	8
Ash removal	Cleaning the ash pit	20 h	100 h	5

4.16. Variable gas flow rate

A diesel engine was modified to work on producer gas. The compression ratio of the engine was reduced to 12. The diesel injection system was replaced with a spark ignition system. An electronic governor was introduced to the engine to control the fuel mixture intake. The electronic governor was coupled with a magnetic pick up to sense the engine speed. Producer gas and air was fed to the engine through a manifold to maintain the air fuel ratio and uniform fuel mixture. The variation in gas quality was minimized due to the fuel wood dryer incorporated in the system. The electronic governor coupled with a throttle valve controls the gas flow depending upon the load and gas quality.

4.17. Up scaling the system for large-scale dissemination and use

The improved dual fired gasifier system is having various advantages like, low tar content Zero dust content which will enable to use in IC engines. The dry gas cleaning system eliminates the complexity related to water procurement and wastewater disposal. Hot gas cleaning system reduces the maintenance cycle of the bag-house filter. Increased cold gas efficiency reduces the Specific fuel consumption rate. With these features the dual fired improved downdraft gasifier system can be adopted for a large-scale use of biomass power plants. A typical size of village electrification plants is in the range of 20–50 kW_e. The cost of these systems will be 35000$ and 60,000$. The present system with dual fired gasifier works with the SFC of 1.1 kg kWh^{-1} and power generation cost as 0.09$ kWh^{-1}. This value is 52% of cost reduction, when comparing Ref. [31] and 31% reduction when comparing Ref. [18]. With the SFC of 330 ml kWh^{-1} the power generation cost works out to be 0.3$ per unit, in case of diesel engines. Present system reduces the power generation cost by 70%, when comparing with the power generation cost using diesel. The majority of all the captive power generation plants use the diesel generators, so the savings compare with the power generation cost using diesel. The payback period of the plant works out to be to a maximum of 4.5 years. This is based on the capital cost of a 50 kW_e biomass power plant is at 60,000$, the plant has been operating for 300 days per year and at 8 h a day. The present cost of diesel as 0.9$ L^{-1} and the cost of processed fuel wood as 0.08$ kg^{-1} were considered for estimation of the saving and payback period.

5. Conclusions

The key finding of the study is, the improved 'dual fired downdraft' gasifier reactor III produces a good quality gas comparing with the reactor I and reactor II. With the hot air supply, reactor III reduces the volatile mater of the fuel wood by 64% in stage I itself. The improved dual fired gasifier system produces the gas with a very low tar content, which is 67 mg Nm^{-3} against 711 mg Nm^{-3} of the reactor I. This improved system produces the gas with a very low dust content, which is 53 mg Nm^{-3} against 1360 mg Nm^{-3} at the exit of the reactor I. At the exit of the gas cleaning train the tar content level is 35 mg Nm^{-3} and dust content is nil. The calorific value of the gas is 5.3 MJ Nm^{-3}. The specific gasification rate is 2.8 Nm^3 of producer gas per kg of fuel wood. The cold gas efficiency of the improved gasifier system is 89.7%. The specific fuel consumption is 1.1 kg of fuel wood per kWh against the normal value of 1.5–1.6 kg kWh^{-1}. Biomass to electric conversion efficiency of the system is found to be as 21%. Because of the waste heat recycling and dry gas cleaning, the improved gasification system has a reduced operation and maintenance cycle by a factor of 5. With these features the dual fired improved downdraft gasifier system can be adopted for a large-scale use of biomass power plants.

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Appendix. Nomenclature

SGR	specific gasification rate ($Nm^3\,h^{-1}\,cm^{-2}$)
F_{cr}	fuel consumption rate ($kg\,h^{-1}$)
G_{cr}	biomass fuel to gas conversion rate ($Nm^3\,kg^{-1}$)
A	cross-sectional area of the reactor (cm^2)
T	time corresponding to the gas flow rate (h)
SRT	solid residence time (S)
R_v	volume of the reactor (m^3)
ρ_{bm}	bulk density of biomass fuel ($kg\,m^{-3}$)
GRT	gas residence time (S)
V_{fb}	void fraction of the biomass fuel used for gasification
G_{fr}	volumetric flow rate of gas ($Nm^{-3}\,S^{-1}$)
η_{cg}	cold gas efficiency of the gasifier system (%) energy fraction
Q_g	quantity of gas produced (Nm^3)
C_g	calorific value of the producer gas ($MJ\,Nm^{-3}$)
W_f	mass of the fuel wood used for gasification in (kg)
M_c	moisture content of the fuel wood used for gasification (%) mass fraction
C_f	calorific value of the fuel wood ($MJ\,kg^{-1}$)

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