Power productivity enhancement using performance analysis of biomass gasifier at energy park, RGTU Bhopal (MP, India)

Prashant Baredar*, Mukesh Pandey, Savita Dixit, Anil Kumar

(*Maulana Azad National Institute of Technology, Bhopal-462 051, India*)

Abstract: The concept paper represents possible opportunities for strategic investment in remote area development and further due attention is paid to determine its feasibility. We examined the status and performance of biomass gasification unit for electricity generation fuelled by woody biomass installed at Energy Centre, Rajiv Gandhi Technological University Bhopal, (India). The main objective of the research project is to utilize the resources of existing biomass feedstock and make performance analysis under purpose of fulfilling the electrical demand of Energy Centre Rajiv Gandhi Technological University Bhopal (India) and rural users in powering of their home lighting, by means of renewable energy. The results of the work will be useful for the future engineering development of biomass gasification unit power generation technologies.

Keywords: biomass, gasification, co-generation, pyrolysis, combustion, India

Citation: Baredar P., M. Pandey, S. Dixit, and A. Kumar. 2013. Power productivity enhancement using performance analysis of biomass gasifier at energy park RGTU Bhopal (M. P. India). Agric Eng Int: CIGR Journal, 15(3): 127−135.

1 Introduction

Biomass is an important source for the generation of energy. This concept is certainly not new. Humans have been burning wood for cooking and heating for thousands of years and many still do. After fossil fuels, biomass is the fourth largest source of energy (Chopra and Jain, 2007). More recent concept is the generation of electricity from biomass gasification. It is difficult to say for certain how extensive the use of biomass is as an energy source today because some of the more traditional and non-commercial uses tend to be hard to account accurately or go unreported. However, some statistics state its current share to the global energy mix between 10%-14% (between 33%-35% on average in developing countries and as high as 90% in the poorest nations like Congo, Liberia etc (Mishra et al., 2010). Worldwide, biomass is the fourth largest energy resource, providing 14% of the world's energy needs approximately (Hall et al., 1992). Utilization of rice husk, sawdust and charcoal for fuel have made these products more valuable rather than considering them as agricultural wastes (Bello and Adegbulugbe, 2010).

In developing countries, usage of biomass accounts for approximately 35% of the energy used, and in the rural areas of these nations, biomass is mostly the only accessible and affordable source of energy. Biomass can be converted into liquid, solid and gaseous fuels with the help of some physical, chemical and biological conversion processes (Demirbas, 2001, 2002).

Most of the biomass power plants in the world use direct-fired systems. They burn biomass feed stocks directly in the gasifier to produce steam that is captured by a turbine, and then converted into electricity by a generator. The steam can also be used for certain other manufacturing processes. Gasification systems require high temperatures and an oxygen-starved environment to convert biomass which is usually wet organic domestic waste, organic industrial wastes, manure, sludge etc., into a gas (a mixture of hydrogen, carbon monoxide, and methane). This gas fuels a gas turbine, which runs an electric generator. Down draft gasifier with throat is

Received date: 2008-10-21 **Accepted date:** 2013-09-04
* **Corresponding author: Prashant Baredar,** Tel.: +91-09406511666, Email: prashant_baredar@yahoo.com.

known to generate best quality producer gas for engines having minimum tar. (Jain 2006)

For large-scale gasification projects the gas is thoroughly cleaned before its combustion. Currently, biomass gasification is considered as one of the most promising thermo chemical technologies and experimental results are presented for gasifier (Zainal et al., 2001).

There are a huge number of different biomass types for use in a gasifier, each one with different properties, including size, shape, bulk density, moisture content, energy content, chemical composition, ash fusion characteristics, and homogeneity of all these characteristics. Coal and petroleum coke are used as primary feedstock for large gasification plants. Moreover, different biomass and waste-derived feedstock can be gasified, with wood briquettes and chips, waste wood, plastics and aluminium, Municipal Solid Waste (MSW), agricultural and industrial wastes, sewage sludge, switch grass, unwanted seed corn and other crop residues all being used.

2 Status and achievement in biomass power sector

In India, the share of various biomass resources, i.e. agricultural residues, animal dung, forest wastes, fire wood, etc., is about 46% of the total energy consumption. India produces a large quantity of agricultural residues, which can be converted into useful energy (TERI Report No.2000RT45). An old practice of direct burning of agricultural residues to generate energy for domestic use is very inefficient. In this context gasification of biomass for electrical power generation, water pumping and thermal applications are important.

Biomass is available in the country in huge quantities in the form of agricultural residues and forestry. Every year more than 500 million tones of crop residues are produced, a large portion of which is either wasted or used inefficiently. Estimates indicate that with the effective utilization of these residues and by using the surplus biomass material, more than 16,000 MW of electrical power can be generated. Further, approximately 3,500 MW of power can be produced if all the 430 sugar mills in the country switched over to modern techniques of co-generation. According to preliminary estimates, the country has a biomass power potential of approximately 19,500 MW.

3 Different heating zones in gasification

Gasification is the process in which biomass is converted into clean and combustible gas in the presence of steam and air. There are different sorts of gasifiers like updraft, downdraft, cross draft and fluidized bed gasifier (Khummongkol and Arrunlaksadamrong, 1990). A description of the reactions that take place in each zone is discussed here. This states that the separate formation of different product classes may be questioned from the viewpoint of analytical chemistry. (Antal, 1985)

- **Drying and heating zone.** In the upper zone fresh biomass is partially dried by the hot gasses rising through the gasifier. The drying process does not change the particles chemically. It is possible to gasify fuels with moisture contents up to 50% but of course, for a high efficiency low moisture content is desired (Demirbas, 2001).

- **Combustion zone.** In the combustion zone, charcoal combusts with oxygen in the air from the inlet at the bottom of the gasifier (Equation (1)) (Ptasinski et al, 2007).

$$C + O_2 \rightarrow CO_2, \Delta H = -393.5 \text{ kJ mol}^{-1} \quad (1)$$

Also some other reaction occur, but at a much lower rate. The effects of these reactions are small and these will not be modeled.

- **Reduction zone.** By the release of CO_2 and heat from the combustion, reduction occurs. The main reaction here is CO being formed from CO_2-molecules and charcoal. This is an endothermic reaction that hardly takes place at temperatures lower than 800°C (Equation (2)) (Ptasinski et al., 2007).

$$C + CO_2 \rightarrow 2CO \text{ (Boundary reaction) } \Delta H = 172.6 \text{ kJ mol}^{-1} \quad (2)$$

- **Pyrolysis.** In the third zone pyrolysis takes place. Pyrolysis is the degradation (lysis) of a material by heat (pyro). The absence of air in this zone, and the high temperature of the gas coming from underlying zones (between 200°C and 500°C) are needed for the gasification of the biomass. Apart from charcoal, also various gas products are formed, mainly including CO, CO_2, H_2O, H_2 and CH_4.

However, in this project, the exact content of the product gas will be left aside.

- The mechanism of pyrolysis is very complex and much research is done towards the weight reduction of a heated particle in thermo gravimetric analysis (TGA) several researchers have developed models for pyrolysis of biomass. (Bamford et al., 1946, Fan et al., 1977, Liliedahl and Sjostrom, 1998, Jalan and Srivastava, 1999)

- Results from these researches are not useful for the dynamic model that will be developed in this study. But they indicate that it is reasonable to calculate the reaction rate of pyrolysis in the same way as the two chemical reactions. One should mention that some in-homogeneities are not modeled this way, such as the effects of the cellulose in the material that will evaporate much slower than other structures in the solid material (Demirbas, 2002). Also the geometries of the wood blocks will cause in- homogeneities in operation in practice. The kinetics of gasification reaction is complicated: in the gasifying process, thermal pyrolysis, homogeneous gas phase and heterogeneous gas-solid reactions take place, so that thousands of chemical reactions may occur (Kovacik et al., 1990).

4 Materials and methods

The final decision about the appropriate electricity supply system for the Energy Centre Rajeev Gandhi Technological University Bhopal M.P. (India) should be based upon the assessment of each option with respect to a set of decision criteria. For this pilot project study, the following criteria have been adopted for the selection of 10 kW biomass gasifier for electricity generation.

- System simplicity and reliability: This criterion is more complicated to measure and is related to various factors, including previous performance of a gasifier technology in a related environment and local experience.

- Organizational: This criterion has to work with the overall electricity supply structure within the University areas. Considering several socio-economic issues, such as which organizational entity undertakes overall responsibility for the system, how easy it is to implement a particular electrification scheme, tariff system, financing opportunities, etc.

- Economic cost: Various cost such as initial investment cost, operation and maintenance cost that should be considered while making cost benefit analysis. It is required to mention that as autonomous system constitutes previously established alternative for isolated power production there are variety of developed tools for dimensioning this system. In the performance analysis, various parameters such as weight, airflow, gas output biomass consumption, gasification efficiency, temp. at different location are measured.

To fulfill electricity requirements of street light in the Energy Park, University Institute of Technology, Rajiv Gandhi Technological University Bhopal, 10 kWe biomass gasifier was installed (Figure 1). The performance of the 10 kW biomass gasifier is monitored throughout the year.

Figure1 10 kW biomass gasifier installed at energy park UIT-RGTU Bhopal

4.1 Biomass for gasification

The wood pieces of rectangular/cylindrical shape of two different sizes were used for evaluation of gasifier. The sizes of the wood pieces selected for the test were as follows: The wood pieces of 20 to 25 mm and 40 to

45 mm cross-sections length were selected for processing the wood. The wood pieces of 20 to 35 mm length were got cut from the commercially available saw cutting machine. The wood having fairly uniform diameter from 20 to 40 mm was also selected for preparation of feed for gasification. The rectangular strip and other wood logs were cut in to the desired size in sawmill and finally segregated manually in to undesired size of wood for gasification. Although wood is a clean fuel with low nitrogen, sulphur and ash content, it is thermally unstable which may lead to formation of condensable tars in gasifier, thus giving problems in down-stream equipment such as choking and blockage of piping (Devi et al., 2003). Producer gas as a fuel in a spark ignited engine has been addressed by a few researchers. (Martin and Wauters, 1981; Parke et al., 1981)

4.2 Measurement of airflow

The average velocity of air entering into the gasifier from gas inlet pipe was measured using digital vane type anemometer. The details of the anemometer used during the study are given below:

Make: LEDA 1000 Electronic Anemometer

Velocity range: 0.2 to 8.0 ms^{-1} and 1.5 to 25.0 ms^{-1}

Air flow rate [m^3 h^{-1}] = Av. Velocity of air [m s^{-1}] × Area of air inlet pipe [m^2]×3600

Where, area of inlet pipe $A = \frac{\pi D^2}{4}$, D is the diameter of pipe, m.

4.3 Measurement of gas output

The producer gas generated by the gasifier was measured at the outlet of the chimney. The velocity of gas leaving the gasifier was measured using hand held vane type anemometer. The distance traveled by the gases in one minute was measured using hand held vane type anemometer and gas velocity was calculated. The average velocity of the gas was multiplied by the area of chimney outlet to measure the gas output in m^3 h^{-1}. m s^{-1} Laune Instruments Limited, Boone Street, London SE 125SA, manufactured the vane type anemometer. The average velocity of the gas at the outlet of gasifier was also verified using soap bubble method.

Gas flow [m^3 h^{-1}] = Average Velocity of air [m s^{-1}] × Area of gas outlet pipe [m^3]×3600

4.4 Measurement of moisture content

Moisture content was determined by oven drying method. Samples were dried at the temperature of 110°C for 24 h. The moisture content was determined by using of following Equation (3):

$$\text{Moisture content} = \frac{W_w - W_d}{W_w} \times 100\% \tag{3}$$

where, W_w = weight of moist sample, g; W_d = weight of dried sample, g.

4.5 Measuring weight of biomass

The woody biomass which is to be fed through hopper should be weighed properly. A platform balance makes average capacity 0 – 110 kg having least count of 100 g were used for weighing the biomass for filling into the gasifier.

4.6 Volume of reactor

The volume of reactor has been estimated as Equation (4):

$$\text{Volume of reactor (V)} = \frac{A \times q}{\rho} \tag{4}$$

where, A = time to operation, h; q = biomass consumption, kg h^{-1}; ρ = Density of biomass, kg m^{-3}.

4.7 Biomass consumption

The biomass consumption was measured using tank fill method. The gasifier was made completely empty before the start of the test and the required size of biomass after weighing was filled up to the neck of gasifier. The total weight of the biomass filled up to the neck of Gasifier was measured. As soon as the gasifier was fired the flammable quality of the gas starts generating the biomass was again filled up to the neck. The time required to burn biomass filled up to the neck of gasifier was measured to determine the average biomass consumption in kg h^{-1} (Equation (5))

$$\text{Biomass consumption} \quad q = \frac{Q}{Hw \times \eta} \tag{5}$$

where, q = Biomass consumption, kg h^{-1}; Q = Total heat required, MJ h^{-1}; H_w = Lower heating value of the biomass, MJ kg^{-1}; η = Expected efficiency of gasifier, %.

Great area is Equation (6) and Equation (7)

$$A = \frac{q}{SGR} \tag{6}$$

where, A = Grate area in m^2; q = Biomass consumption, kg h^{-1}; *SGR* = Specific gasification rate of biomass, [kg/h- m^2].

$$SGR = \frac{\text{Weight of dry biomass used per hour (kg h}^{-1}\text{)}}{\text{Cross sectional area of the gasifier reactor}} \quad (7)$$

For producing energy rich fuel producer gas, the consumption of the biomass is recorded and at various biomass consumption values, gasifier efficiency is calculated. At biomass consumption 3.8 kg h^{-1} gasifier efficiency was 77%.

4.8 Estimation of gasification efficiency

Gasification process converts solid fuel into a gaseous fuel through a process of high temperature oxidation-reduction reactions. Combustion process converts solid fuel into gaseous products of combustion through high temperature oxidation reactions.

Gasification efficiency =

$$\frac{\text{Gas output [m}^3\ \text{h}^{-1}] \times \text{Lower calorific value of producer gas [MJ m}^{-3}]}{\text{Biomass consumption[kg h}^{-1}] \times \text{LCV of biomass[MJ kg}^{-1}]}$$

where,

Biomass consumption [kg h^{-1}] =

$$\frac{\text{Total biomass consumption [kg]}}{\text{Time required to consume the biomass[h]}}$$

4.9 Measurement of temperature profile inside the gasifier

The temperature profile of gasifier was measured using chrome-allumel thermocouples at four different locations i.e. 20 mm, 120 mm and 700 mm above the grate. The output of the thermocouples was measured in mV and the output of mV was converted into temperature using the standard table for the conversion (Burns et al., 1993). The ambient temperature added to the measured temperature for the temperature compensation in thermocouples. The digital temperature indicators made Altop and Fluke was also used to measure the temperature inside the gasifier. In the temperature indicator the ambient compensation was automatic added. The details of the portable temperature indicator are given below:

Make : Fluke, 54 series II made in Netherlands
Channel : Two
Accuracy : ± 1°C
Sensor: Thermocouple (JK & S type)

5 Results and discussion

Gasifier when connected with electric generator through engine can generate electricity. It is observed that in the month of March, April and May, the value of power generation was peak due to less moisture content in the woody biomass. There should be minimum moisture content for proper gasification. The electricity produced from a biomass-based gasifier system can be used for lighting houses, powering irrigation pumps, and operating machines such as chillers (Figures 2 and 3).

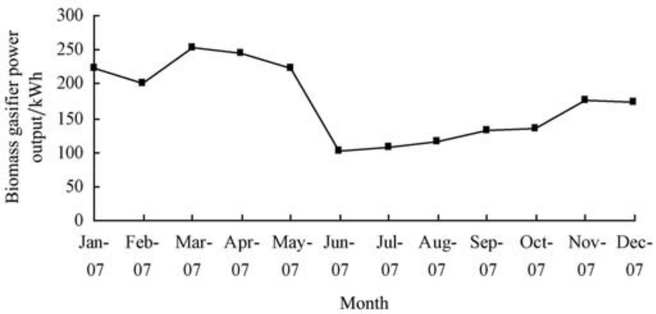

Figure 2 Month wise biomass gasifier power output throughout the year

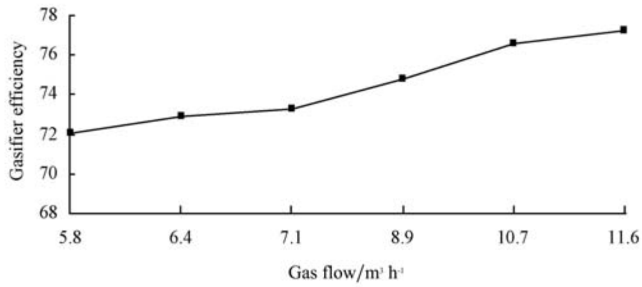

Figure 3 Efficiency of gasifier variation with gas flow

Gas flow of the producer gas obtained from the biomass gasifier is collected and at different gas flow, biomass gasifier efficiency was calculated at 11.6 $m^3 h^{-1}$. Gasifier efficiency was 77%. With the increase in gas flow rate the efficiency of gasifier increases and becomes steady for a particular value and then started decreasing after particular gas flow rate as the flow diameter got choked. The maximum increment of the efficiency occurs from 7.1–10.7 $m^3 h^{-1}$. This mainly showed that gas having clean composition of producer gas also affects the efficiency. Gas flow of the producer gas obtained from the biomass gasifier is collected and at different gas flow, biomass gasifier efficiency was calculated at 11.6 $m^3 h^{-1}$. Gasifier efficiency was 77% (Figure 4).

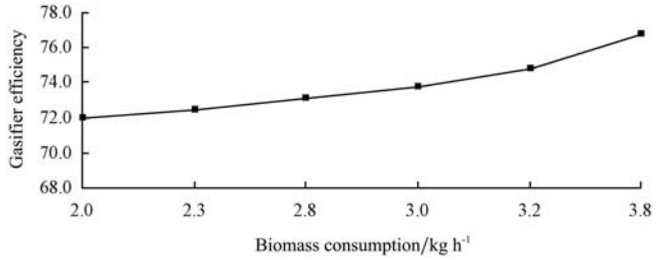

Figure 4 Efficiency of gasifier variation with biomass consumption

Efficiency of the gasifier depended upon the type of biomass used. Mainly the types of biomass were wood, rice husk, agricultural & domestic waste. The efficiency increased steadily up to 3.2 kg h^{-1} but it rapidly increases from Figure 2, Figure 3 and Figure 4. This was mainly due to decrease in the moisture content in the biomass as the heat produced in gasifier was used up in reducing the moisture of the rest of bio-fuel. Large consumption of dried biomass shall result in greater efficiency . Grate was the area where combustion of fuel took place. Maximum temperature occurred just above the bottom surface of the grate. As went above the grate the temperature of the flame decreases due to loss in heat on account of radiation and convection losses. The temperature fall was steady up to a certain distance then it fell linearly with greater slope because of the char and carbon content it is not mixed with the air (Figure 5).

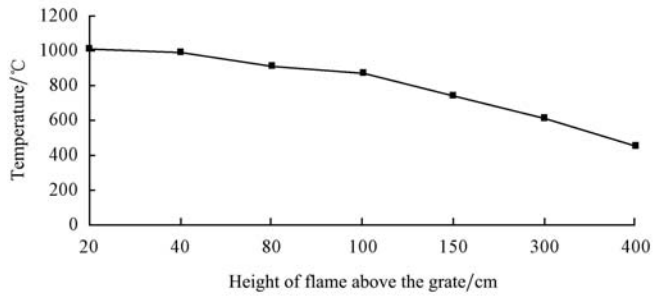

Figure 5 Temperature variations with height of flame above the grate

In the combustion chamber, the burning flame height is observed as shown in graph and the value of temperature at respective flame height is plotted.

A. Gas outlet temperature: The temperature of the producer gas leaving the Gasifier was measured at the outlet of the chimney using thermocouple. The temperature was measured when the gasifier started producing flammable gases (Figure 6).

Figure 6 Gasifier flame produced in 10 kW biomass gasification system

B. Flame temperature: The flame temperature of the gases burning in the developed burner was measured using thermocouple with temperature indicator while measuring the temperature air drift to the burner was avoided. The maximum temperature of the flame was measured by shifting the thermocouple in different locations of the flame. In the combustion chamber flame temperature changed with the time. At different time from the flame initiation, the flame temperature was recorded and plotted (Figure 7).

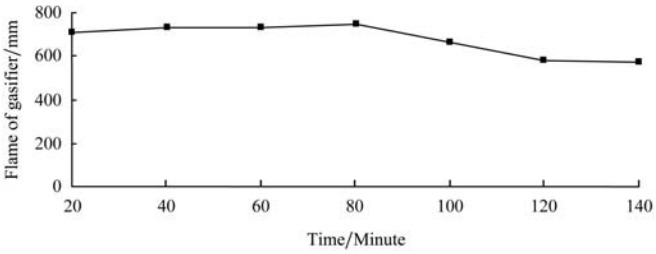

Figure 7 Flame of gasifier variation with time

The flame temperature of gasifier changed with the time. The variation in the gasifier flame with time was recorded and plotted and flame speed depended upon the quantity of the fuel used. In the beginning the flame speed increased slightly as we add more amount of fuel. After certain time the back pressure of the of the flame increases and hence the flame speed decreased noticeably. After certain period the flame becomes steady due to continuous mass flow rate (Figure 8).

The above graph shows the temperature profile of the various parameters such as grate temperature, flame temperature, gas outlet temperature. The temperature produced at the grate due to combustion of the fuel (biomass) varied almost linearly with the time. It increased at very slight level in the starting and went up to 1,300°C at the 50th min and then decreased due to heat taken up by the moisture. But this decrease was not affected due to continuous working of the gasifier and the temperature again increases and became constant at the grate level of the gasifier. The flame temperature remained almost constant due to continuous working of the gasifier. It attained the maximum value of 825°C with slight variation which may be due to grate design, internal design of the gasifier, moisture content of the fuel etc.

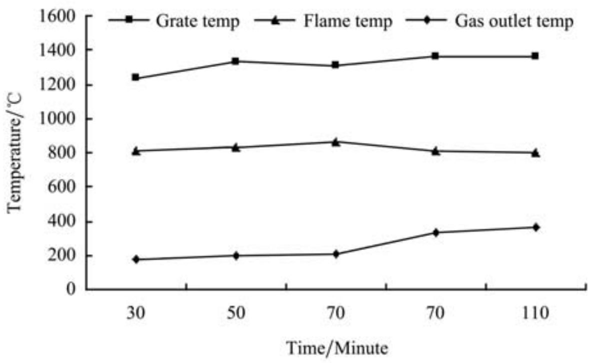

Figure 8 Graph of various temperature of gasifier variation with time

During the running condition the temperature of the flame was almost constant. As the fuel gas mainly contained the producer gas and some traces of methane, ethane etc., these gases contained the large quantity of hydrogen. So the temperature of the flame was very high (around 800°C) but lower than the temperature of grate (as the flame losses heat due to convection, conduction and radiation).

The outlet temperature of the gas was less than the flame temperature and the grate temperature as the gas coming out of the gasifier has lost its heat in various zones after 30 min the starting temperature was 200°C. This temperature remains constant for about 70 min and then it has increased to 360°C because of the continuous working condition heat dissipation rate has gone under equilibrium condition with the heat of the outlet gas temperature after 110 min the temperature of the gas was at highest i.e. 400°C

6 Impact of moisture content on biomass gasifier performance

Changes in wood moisture were well tolerated by the process. During the testing program, as feedstock moisture levels were changed from level to another, the gasifier and combustor reactors responded within minutes to the changes. When large changes in moisture content were made rapidly (20% to 30% by volume), gasifier and combustor temperatures change more significantly so that a final steady state temperature, at each condition, was slightly delayed (about one to two hours depending on the magnitude of the moisture change) due to response of the system refractory. Even though the final steady state condition required some time to be reached, the gas production rate adjusted within minutes to within +/- 5% of the final equilibrium value.

Likewise, incoming wood feed rates can be changed as rapidly as required to match load requirements. The rapid system response to changes in system inputs allowed the process to operate with a relatively wide turndown capability. The limitation on feed rate change was determined by feed system capabilities, not the gasification process. Additionally, the throughput of the vessels had an impact on overall process economics (Saravanakumar et al., 2007). Tests were run to evaluate the maximum throughput of wood to the plant. These tests showed that wood feed rates of over 350 dry tones per day could be achieved with no degradation in system performance. The results indicate that plant turndown capability is at least 1.5 to 1. Higher feed rates were limited by the capacity of the feed system in the plant.

The temperature of gas exiting the reactor was about 600-900 K. The typical composition of the gas is 18%-20% H_2, 18%-20% CO, 2%-3% CH_4, 12% CO_2, 2.5% H_2O, and rest 52.5%-57.5% N_2.

The gas generated in the reactor of a gasifier was at a high temperature, and carried along with it tar and ash, which were undesirable particularly for IC Engine. Tar sticked to surfaces and caused jamming of moving parts and blockage of small passage and ashes and other solid particle would aggravate the problem further. Further, high temperature of the producer gas reduced the volumetric efficiency of an IC engine. Hence the cooling and cleaning of producer gas was necessary before its use for electrification.

Dust can be removed from gases by using cyclones, scrubbers or filters. Cyclones are used when the gas flowed at high velocity, and when particle sizes were greater than 15-20 microns. Scrubbers were used for tar removal as well as particle removal. Filters can be used for this purpose. Wet scrubbers can also be used for gas cooling. It was necessary to replace the filter material after specific period to prevent its clogging with tar.

7 Conclusion

The performance analysis of biomass gasification unit was carried out. It was observed that the temperature remained steady nearly along the drying zone, with a little augment, just in the hardly any final centimeters. This is due to the fact that in most of the length of the drying zone, the gas absorbs the biomass moisture, as primary stage, causing no enhance in biomass temperature, and, in the next stage, when all the moisture has been taken away, the biomass temperature raises up to its outlet temp. The experimental data obtained in the drying process indicating time disparity of measured biomass temperature inside the drying zone, indicates an increase in temperature is observed during the first few minutes, and then it remains approximately steady with some slight variations along the drying zone. The 10 kW gasifier project examined in this paper demonstrates that this system is technically confirmed, competent, and reasonably viable when put in the right setting. Working limitations like a sustainable biomass supply and energy distribution have to be straight away addressed and business models needed to be prepared.

Thus from the above observation it was cleared that how feasible the biomass gasification unit for generating the electricity to fulfill the electrical demand of Energy Centre, Rajeev Gandhi Technological University Bhopal M.P. (India) and rural users in powering of their home lighting, by means of renewable energy was. The future of biomass electricity generation lied in biomass integrated gasification/gas turbine technology, which offers high energy conversion efficiencies. The electricity was produced by direct combustion of biomass, advanced gasification. And pyrolysis technologies were almost ready for commercial scale use. A supplementary firing of biomass in steam-electric power plants may under certain circumstances, prove to be economically feasible.

Acknowledgement

The authors are very much thankful to All India Council of Technical Education (AICTE) for sponsoring under research promotion scheme (RPS). The authors gratefully acknowledge to the Vice Chancellor Dr. Piyush Trivedi of the Technical University of M.P. India for their kind permission and directions to conduct the experimentation and research work on Integrated Renewable Energy System (Biomass Gasifier / Gas Engine Gen-set) located at Green Power Technology Centre of RGTU, MP. India.

References

Chopra S. and A Jain. 2007. A review of fixed bed gasification systems for biomass. *CIGR Journal,* 9(5).

Mishra P., P Singh, P. Baredar. 2010. Impact of moisture level in atmosphere on biomass gasification: A Bio energy for sustainable development. *International Journal of Environmental Sciences,* 1 (4):640-644.

Hall, D.O., F. Rosillo-Calle, and P. De Groot. 1992. Biomass energy--lessons from case studies in developing countries. *Energy Policy,* 20(1): 62-73.

Bello, S. R., and T. A. Adegbulugbe. 2010. Comparative study on utilization of charcoal, sawdust and rice husk in biomass furnace-dryer. *CIGR,* 12(2).

Demirbas, A. 2001. Biomass and the other renewable and sustainable energy options for Turkey. *Energy Conversion. Mangement*, 40:743-755.

Demirbas A. 2002. Production potential of electricity from biomass in Turkey. *Energy Sources*, 24:921-929.

Jain, A. K. 2006. Design parameters for a rice husk throatless gasifier reactor. *CIGR Journal, 8.*

Zainal, Z. A., R. Ali, C. H. Lean, and K. N. Seetharamu. 2001. Prediction of performance of a downdraft gasifier using equilibrium modeling for different biomass materials. *Energy Conversion, Management*; 42: 1499–1515.

Biomass power, TERI Report No.2000RT45, pp.39-40.

Khummongkol D., and W. Arrunlaksadamrong. 1990. Performance of an updraft mangrove–wood gasifier, *Energy,* 15(9): 781-784.

Antal, M.J. 1985. Biomass pyrolysis: a review of the literature. Part II – Lignocelluloses pyrolysis. In: Boer KW, Duffie J. A., editors. *Advances in Solar Energy*. Boulder, CO: American Solar Energy Society. pp. 175-255.

Krzysztof, J. P., M. J. Prins, and A. Pierik. 2007. ***Exergetic evaluation of biomass gasification***. *Energy,* 32: 568-574

Bamford, C. H., J. Crank, and D. H. Malan. 1946. The combustion of wood. Part I", *Proceedings of the Cambridge Philosophical Society*, 42: 166-182.

Fan, L. T., L. S. Fan, K. Miyanami, T. Y Chen,. and W. P Walawender. 1977. A mathematical model for pyrolysis of a solid particle - effects of the lewis number". *Canadian Journal of Chemical Engineerin*g, 55: 47-53

Liliedahl, T., and K Sjostrom. 1998. Heat transfer controlled pyrolysis kinetics of a biomass slab, Rod or sphere. *Biomass and Bioenergy*, 15: 503-509.

Jalan, R. K., and V. K Srivastava. 1999. Studies on pyrolysis of a single biomass cylindrical pellet- kinetic and heat transfer effects. *Energy Conversion Management*, 40: 467-494.

Kovacik G, M. Oguztoreli, A. Chambers, B. Ozum. 1990 Equilibrium calculations in coal gasification. *Int. J. Hydrogen Energy*, 15(2): 125-131.

Devi, L., K. J. Ptasinski, F. J. J. G. Janssen. 2003. A review of the primary measures for tar elimination in biomass gasification processes. *Biomass and Bioenergy*, 24: 125-140.

Martin, J., and P. Wauters. 1981. Performance of charcoal gas internal combustion engines, *Proceedings of the International Conference – New Energy Conversion Technologies and their Commercialization*, 2: 1415–1424.

Parke, P. P., and S. J. Stanley, and W. Walawnder. 1981. Biomass producer gas fuelling of internal combustion engines. *Energy from Biomass and Wastes V*, Lake Buena VistaFlorida, pp. 499–516.

Burns, G. W., M. G. Scroger, and G. F. Strouse. 1993. Temperature-electromotive force reference functions and tables for the letter-designated thermocouple types based on the IPTS-90 NIST monograph 175". Washington, D.C.: U.S. Department of Commerce.

Saravanakumar, A., T. M. Haridasan, B. R. Thomas, and R. Kasturi Bai. 2007. Experimental investigations of long stick wood gasification in a bottom lit updraft fixed bed gasifier. *Fuel Processing Technology Elsevier*, 88(6): 617-622.