Pergamon

0961-9534(94)00049-2

Biomass and Bioenergy Vol. 8, No. 2, pp. 91–98, 1995

0961-9534/95 $9.50 + 0.00

DEVELOPMENT OF A SUGARCANE LEAF GASIFIER FOR ELECTRICITY GENERATION

RAJEEV M. JORAPUR and ANIL K. RAJVANSHI

Nimbkar Agricultural Research Institute (NARI), P.O. Box 44, Phaltan 415523, Maharashtra, India

(Received 28 September 1992; revised received 11 April 1994; accepted 2 May 1994)

Abstract—This study reports the development of a gasifier running on sugarcane leaves. A 15 kVA diesel generator set was operated for over 200 h using this gasifier. The gas flow rate and calorific value were 3–4 Nm^3 kWh^{-1} and 3.5–5.0 MJ Nm^{-3}, respectively. The cold gas efficiency was 35–60% over the entire range of loads tested (3.5–11.3 kW). The diesel saving (DS) was nearly independent of the load and was 70–93% at a pressure drop (ΔP) of 40 cm water gauge (WG); it reduced to 50–70% at $\Delta P > 50$ cm WG. The indicated thermal efficiency reduced from 18–29% at 3.5–11.3 kW loads, respectively, in the diesel-alone mode, to 16–26% at the corresponding loads in the dual-fuel mode. About 15–28% by weight of the fuel was converted into char with a calorific value of ~ 19 MJ kg^{-1}. This char, when mixed with a suitable binder and briquetted, formed an excellent fuel for wood stoves. An economic analysis using the Levelised Annual Cost (LAC) method showed that such gasifiers are more suited for direct heat applications than for shaft power applications at the present level of technology.

Keywords—Gasification; sugarcane leaves; electricity generation; direct heat applications; loose leafy biomass; char production.

1. INTRODUCTION

Most of the developing countries, including India, rely heavily on imports of crude oil and petroleum products to meet their ever-increasing energy demands. Thus, India imported about Rs. 97 × 10^9 (\$(US)1 = Rs. 30) worth of these products in 1990–1991,[1] which was nearly 20% of its total import bill.[2] This increased to over Rs. 130 × 10^9 in 1991–1992.[3] There is thus a pressing need to identify alternative, indigenous and renewable energy sources.

Biomass fuels in various forms are abundantly available in most of these countries. India alone has a surplus of about 100 million tonnes of agricultural residues every year comprising mainly rice husk, paddy straw, sugarcane leaves and wheat residues.[4] These are presently often disposed of by burning in fields.[4] Apart from the resulting extensive smoke and fly ash problems, this also represents a large loss of energy. Thus biomass-based decentralised energy generation technologies offer an attractive solution to the energy crisis.

Gasification is a promising route to harness this source of energy. Producer gas (mainly comprising carbon monoxide and hydrogen with slight amounts of methane) derived from these residues can substitute 70–90% of the diesel oil used in CI engines for such applications as in irrigation pumpsets, generators, threshers and crushers. Since diesel oil alone accounts for over 42% of the total oil import bill of India,[5] use of producer gas could result in significant reduction in the oil import bill. Further, emission of fly ash and other pollutants from open burning of these residues is greatly reduced in the case of gasification.

Most of the previous work on gasification revolved around the use of charcoal, wood, and to a certain extent, rice husks.[6] However, their limited availability and site specificity, coupled with other competing uses (such as in cooking and the paper and pulp industry), has forced attention on development of technologies for the use of other agricultural residues.

In India, sugarcane is harvested manually. The tops and leaves are stripped from the stalks in the field after cutting the stalks. The tops are extensively used as fodder for animals. However, the dried leaves are disposed of by burning them in the open field, which is a large loss of potentially useful heat energy. Gasification of these leaves offers a better option for their utilisation.

This paper reports the development of a loose sugarcane leaf gasifier, and its utilization to generate electricity in the 3.5–12 kW range through a diesel-oil-powered generator. Though other fuels such as sweet sorghum stalks and bagasse, sugarcane bagasse, wheat straw, cotton stalks and maize residues were successfully gasified using this system,[7] all the data reported here refer to gasification of sugarcane leaves only.

2. MATERIALS

2.1. *Fuel*

Sugarcane leaves were chopped into 1–10 cm long particles using a 2.3 kW (3 h.p.) chaff cutter and air-dried before being fed into the gasifier. Table 1 shows some of the relevant characteristics.

Table 1. Characteristics of sugarcane leaves

Particle size (cm)	1–10
Bulk density ($kg\,m^{-3}$)	25–40
Moisture content (% wet basis)	4–33%
Proximate analysis (% dry basis)	
Volatile matter	77.4
Fixed carbon	14.9
Ash content	7.7
Ultimate analysis (% dry basis)	
Carbon	39.75
Hydrogen	5.5
Oxygen	46.84
Nitrogen	0.186
Ash	7.72
Higher heating value ($MJ\,kg^{-1}$)	16–17.6
Ash deformation temperature (°C)	900

Sugarcane leaves differ considerably from conventional gasification fuels like wood and rice husks on two major counts. Firstly, their bulk density (25–40 $kg\,m^{-3}$) is significantly lower than wood or rice husks (250–330 and 90–110 $kg\,m^{-3}$, respectively[8,9]). Secondly, the ash-softening temperatures are lower for sugarcane leaves (900°C) compared with wood (1050°C) and rice husks (1439°C).[9] Thus, sugarcane leaves are a considerably more difficult fuel to gasify than wood or rice husk.

2.2. *Experimental design*

The experimental system is shown in Fig. 1. It consists of a reactor, a gas conditioning system and a diesel-powered generator along with its control panel. Salient features of these components are given below.

2.2.1. *Reactor*. Conventional reactor designs for wood or rice husk gasification were not found suitable for sugarcane leaves. Their very low bulk density (25–40 $kg\,m^{-3}$ as compared with 250–330 $kg\,m^{-3}$ for that of wood) did not permit uniform biomass flow through the narrow cross-sectional area or the "throat", which is a common feature of conventional wood gasifiers. Moreover, sugarcane leaves tended to flare up within minutes of being fed into the reactor. This made it impossible to maintain a layer of any significant thickness of unburnt fuel inside the reactor. Thus, batch charging of the reactor as in wood or rice husk gasifiers was not found feasible. Thus a "throatless" (cylindrical) gasifier reactor was initially designed and developed at NARI for wood gasification and was subsequently modified for gasification of sugarcane leaves. The details of the development of this reactor design are given elsewhere.[7]

The final reactor configuration was developed after 1200 h of experimentation. It has a 30 cm diameter inner cylinder made of stainless steel SS 304 10 SWG (3 mm thick). The rest of the reactor is made of mild steel MS 16 SWG (1.6 mm thick). All the mild steel components were painted with two coats of red oxide primer to resist corrosion.

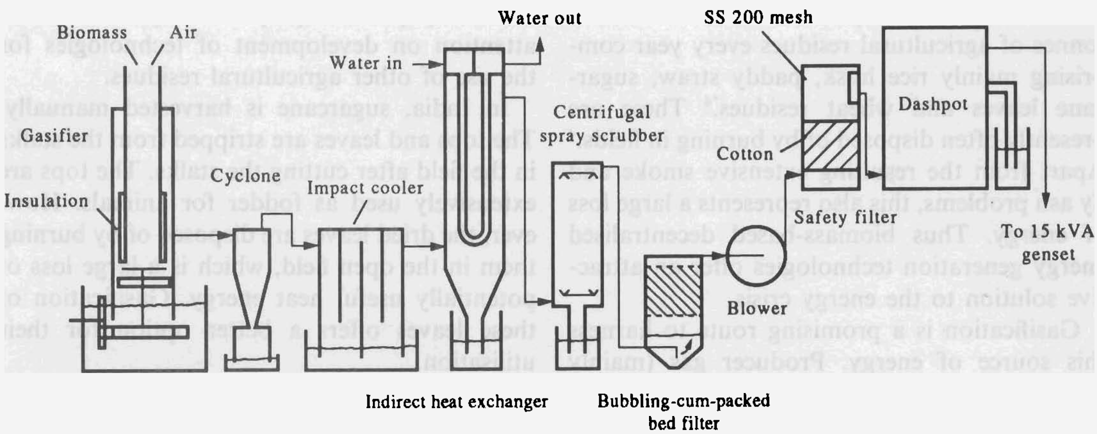

Fig. 1. Schematic diagram of the 15 kVA diesel generating set with the gasifier system.

2.2.2. *Gas-conditioning unit*. In gasification of agricultural residues, there are considerable amounts of particulates, tars and other condensables associated with the gas ($\sim$7–15 g Nm^{-3} of gas produced[7]). If particulates are allowed to enter the engine, they cause increased wear and tear of moving parts, gum up the inlet and outlet valves, increase the corrosion rate of different engine components, contaminate the lubricating oil and, in general, are highly detrimental to the engine performance.[8,9] Thus, an effective gas-conditioning system is required to strip the gas of all these undesirable constituents. This was accomplished by using the system shown in Fig. 1. It consists of a cyclone, an impact filter, an indirect-contact heat exchanger, a centrifugal scrubber and a bubbling-cum-packed bed filter. An additional safety filter containing cotton and a stainless steel mesh (SS 200 mesh) as recommended by Reed and Das[8] was also used to safeguard the engine.

2.2.3. *Diesel generator set*. The generator set has a direct-injected twin-cylinder diesel-powered prime mover with a rating of 14 kW (19 h.p.), and rotating at a constant speed of 1500 r.p.m. This was connected to a 15 kVA alternator with a power factor of 0.8 and which generated electricity at 415 V/50 Hz a.c. The maximum recommended continuous operating load was 10.2 kW. In spite of this, a few data points were generated at 11.3 kW load.

2.2.4. *Instrumentation*. Pressure drops at critical junctures in the system were measured using U-tube manometers. The reactor bed temperatures were measured using a type K (Chromel–Alumel) thermocouple. The gas flow rates were measured to within $\pm 3\ Nm^{-3}\,h^{-1}$ using pre-calibrated orifice meters. The calorific values of solid fuels were estimated using an Emerson non-adiabatic bomb calorimeter and the moisture contents were obtained by oven-drying samples to constant weight. The gas calorific value was measured by a Junkers calorimeter. The electrical load on the generator was provided by a combination of lamps (4.6 kW) and two electric heaters of 4 and 6 kW capacities. An energy meter monitored the actual load on the generator to within ± 0.5 kWh.

3. EXPERIMENTAL METHODS

Both the gasifier and the generating set were started simultaneously. A small amount of sugarcane leaves was first fed into the reactor. A 0.75 kW (1 h.p.) electric blower used to provide suction through the system was then switched on. A lighted ball of cloth/cotton was then dropped inside the reactor. The leaves ignited almost instantaneously. Continuous feeding of sugarcane leaves then commenced. Combustible gas was formed within 3 min after ignition of the char-bed and was flared in a suitably designed burner. (The details of the burner design, where flame temperatures in excess of 1240°C were obtained, are given elsewhere.[7]) The char removal mechanism was activated after the bed height reached $\sim$60 cm above the grate. Subsequently, the char removal and biomass feed were continuous.

During this time, the required electrical load (between 3.5 and 11.3 kW) was provided to the generator (operating on diesel-alone mode) through the control panel. Gas supply to the generator was commenced only after ascertaining that combustible gas was being produced at the burner. The blower was operated even during the generator operation, thereby ensuring a constant gas flow rate even at higher loads (>9 kW). The air–gas mixing was effected through a simple T-junction at the blower outlet before being admitted into the engine manifold (dual-fuel mode). No other modifications were made to the engine.

Process parameters like temperature, pressure drop, gas flow rate, current, voltage and diesel consumption were measured every 15 min and then averaged out over the entire duration of the experiment.

4. RESULTS AND DISCUSSION

The diesel savings (DS), an important indicator of the gasifier–generator system performance, was defined as

$$DS = 1 - (SDC_{df}/SDC_{d}), \qquad (1)$$

where SDC is the specific diesel consumption ($g\,kWh^{-1}$). The subscripts df and d refer to dual-fuel and diesel-alone modes of operation, respectively.

The system was operated for over 220 h. Attempts were made to maximize DS and minimize the specific biomass consumption (SBC), which is defined as kg of biomass consumed per kWh output. Table 2 summarizes the data generated on the 15 kVA generator–gasifier system.

Figure 2 shows the DS obtained at different loads. It is evident that an increased pressure drop of the system resulted in lower DS. Higher pressure drops, usually a consequence of ac-

Table 2. Summary of the gasifier–generator data

No. of hours tested	220
Range of loads tested	3.5–11.3 kW (29–94% of alternator capacity)
Specific biomass consumption (SBC)	1.2–3.5 kg kWh^{-1}
Specific diesel consumption (SDC)	
(a) diesel-alone mode	275–450 g kWh^{-1}
(b) dual-fuel mode	15–150 g kWh^{-1}
Diesel savings	70–92.5% at $\Delta P < 40$ cm WG 50–70% at $\Delta P > 50$ cm WG
Producer gas flow-rate	3–4 Nm^3 kWh^{-1}
Gas calorific value	3.57–5.04 MJ Nm^{-3}
Char production	15–28% of the fuel by weight
Char calorific value	18.9–23.1 MJ kg^{-1}
Total contaminants in gas	
at gasifier outlet	7–15 g Nm^{-3}
after safety filter	10–150 mg Nm^{-3}

cumulation of contaminants in different components of the gas conditioning system, imply leaner gas to air mixtures (due to lower gas flow rates) and hence result in lower *DS*. This phenomenon may be partially responsible for reported incidences of low *DS* especially at higher loads.[11,12]

Further, *DS* is fairly independent of the load, and lies between 70 and 92% (for $\Delta P < 40$ cm WG) throughout the range of loads tested (3.5–11.3 kW). This is primarily because low pressure drops and adequate gas flow rates even at higher loads were possible due to the use of the blower even during the generator operation. In fact, higher gas flow rates (3.5–4 Nm^3 kWh^{-1}) resulted in very high *DS* (>85%). However, this was almost always accompanied by severe "knocking" of the engine, especially at lower loads (<7 kW), and hence it was thought advisable to limit the gas flow rate, and thus the *DS*, to 3 Nm^3 kWh^{-1} and 80–85%, respectively.

Figure 3 shows the relationship between SBC and load. The trend towards declining SBC at higher loads (3.5 kg kWh^{-1} at 3.5 kW and 1.2 kg kWh^{-1} at 11.3 kW) is similar to that reported by others,[12,13] and clearly demonstrates the need to operate the generator at near maximum load conditions. This finding is further corroborated from the plot of the indicated thermal efficiency (η_t) of the prime mover vs load shown in Fig. 4. η_t is defined as

$$\eta_t = (CV_g \times V_g + CV_d \times SDC_d)^{-1}, \quad (2)$$

where CV_g is the gas calorific value (kWh Nm^{-3}), V_g is the specific gas flow rate (Nm^3 kWh^{-1}), CV_d is the diesel calorific value (kWh kg^{-1}), and SDC_d is the specific diesel consumption (kg kWh^{-1}).

It is seen from Fig. 4 that η_t increases with increasing load and reaches a maximum of 29% at 10 kW. It is also evident that η_t is lowered by 3–5% when operating in the dual-fuel mode as

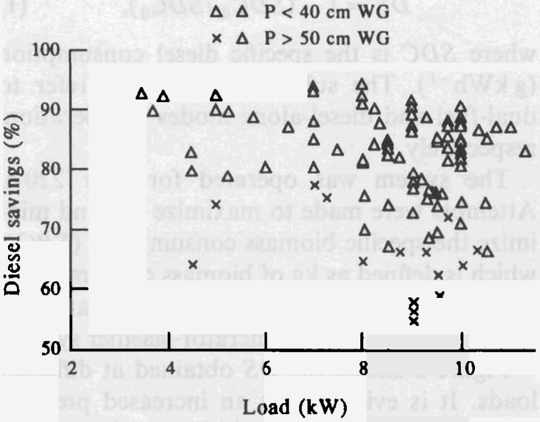

Fig. 2. The diesel savings (*DS*) obtained at different operating loads on the diesel generating set (WG = water gauge).

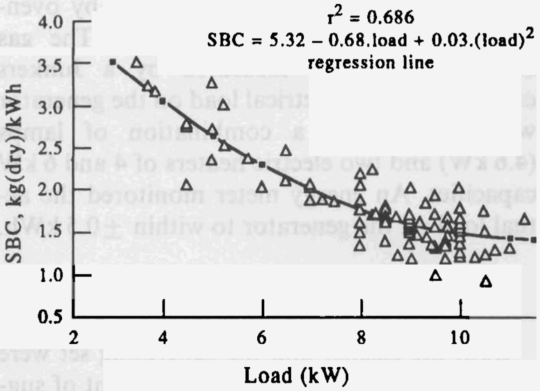

Fig. 3. The specific biomass consumption (*SBC*) plotted against the corresponding load. *SBC* = biomass consumed (kg, dry)/net electrical output (kWh).

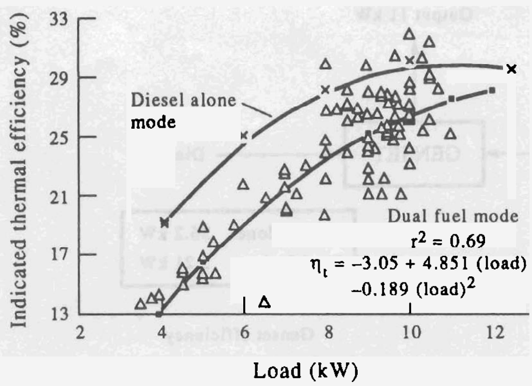

Fig. 4. Indicated thermal efficiency (η_t) vs load.

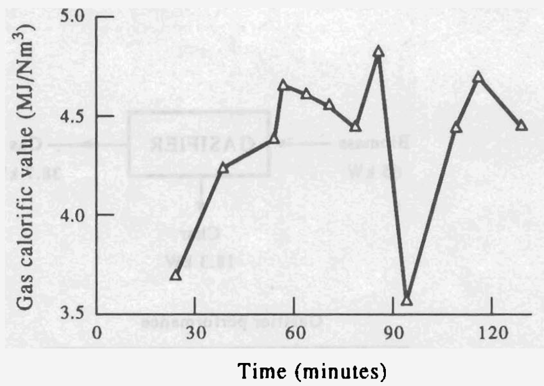

Fig. 5. Variation of the gas calorific value with elapsed time after ignition of the gasifier.

compared with diesel-alone mode. This inefficient combustion of the mixture of gas, diesel oil and air inside the cylinder block was attributed by Kaupp and Goss[13] to its lower flame speed as compared with that of the diesel oil–air mixture normally present in the engine chamber. Another factor contributing to the lower efficiency in the dual-fuel mode is the considerable, and frequent, changes in the gas calorific value (CV). This is shown in Fig. 5, where the CV varied from 3.5 MJ Nm^{-3} ($\sim$850 Kcal Nm^{-3}) to 4.83 MJ Nm^{-3} ($\sim$1150 Kcal Nm^{-3}) even during the course of a 130 min run. Since the stoichiometric requirement of air for complete combustion of gas is strongly dependent on its composition and hence CV, this phenomenon required that the air (and hence diesel) flow rate be continually monitored to maintain an optimum mix of gas, air and diesel flow rates in the combustion chamber. However, in the absence of any sophisticated control system, this was not possible, and hence, lower efficiencies were inevitable. In spite of this large variation in the gas calorific value, the generator output was steady. It was able to absorb this variation in the gas calorific value by suitably altering the diesel consumption.

Figures 6 and 7 show, respectively, the material and energy flow diagrams of the overall system. It is seen that nearly 25% by weight of the input fuel ($\sim$28% of the input energy) is converted into char. A typical proximate analysis of the char from sugarcane leaves[10] showed a volatile matter content of 17%, fixed carbon content of 43.8% and ash content of 39.2%. It had a higher heating value of 19 MJ kg^{-1}. This char, when mixed with a suitable binder and briquetted, forms an excellent fuel for wood stoves.[5,10] Water boiling tests conducted on a typical stove gave thermal efficiencies of $\sim$11–15% with these briquettes as compared with $<$10% on wood. Wood stoves are commonly used for cooking in rural areas of Third World countries. Extensive deforestation and other competing uses of wood have resulted in its scarce availability for cooking. It is in this context that production of char from abundantly available and largely untapped agricultural residues assumes added importance.

The energy flow diagram (Fig. 7) shows that about 60% of the input energy is converted into gas and about 28% into char. Skin losses through the body of the reactor account for

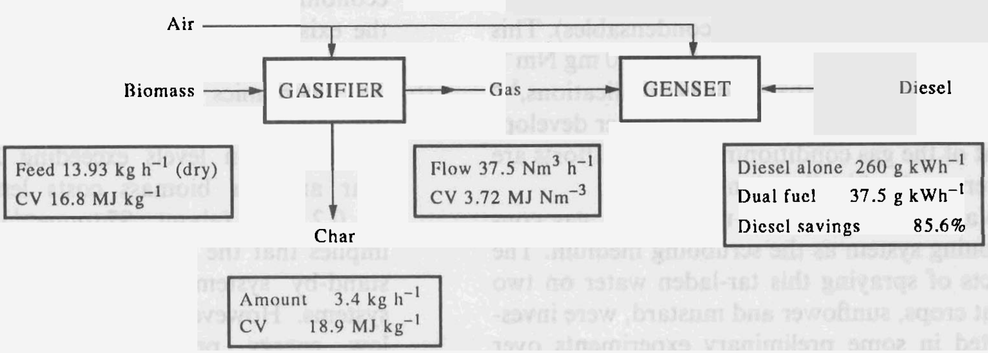

Fig. 6. Material flow diagram of the generator–gasifier system.

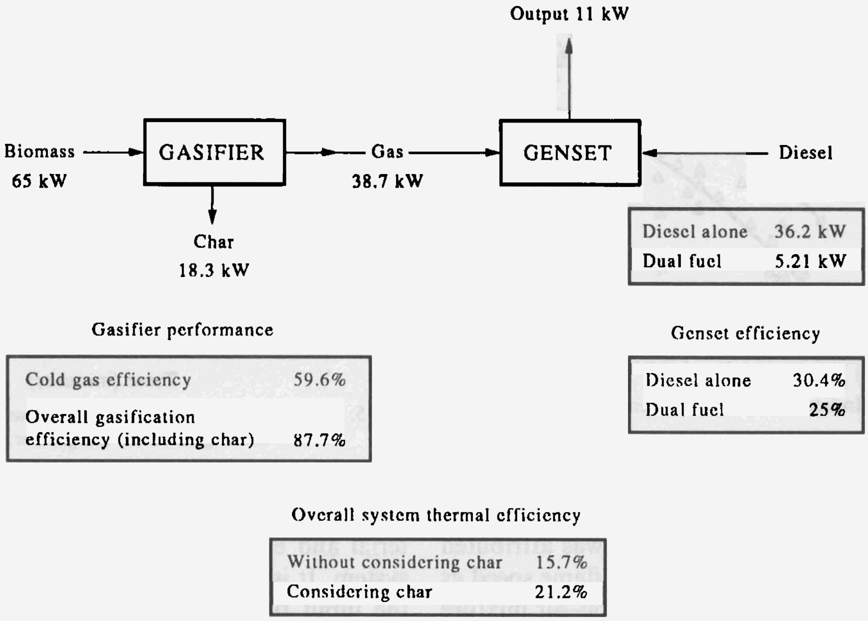

Fig. 7. Energy flow diagram of the generator–gasifier system.

~2–3%. The major loss, however, is in cooling the gas from 350° to ~30°C. This sensible heat loss accounts for nearly 9% of the input energy. The overall system thermal efficiency was 15.7% without considering the char as a useful by-product. If the char is taken into account the overall efficiency becomes 21.2%.

Long-term testing of the gasifier–generator system has clearly shown that stainless steel SS 304 10 SWG (3 mm thick) is not a suitable construction material.[10] It suffered extensive deformation and had to be replaced after only 750 h of operation. This included about 200 h of operation with the generator and 550 h without the generator when the gas cleaning system was being developed. The details of this are given elsewhere.[7] Thus, other materials, such as ceramics, are being examined.

It is also seen from Table 2 that the gas downstream of the security filter unit still contained 10–150 mg Nm^{-3} of total contaminants (particulates, tars and other condensables). This is in excess of the maximum of 10–100 mg Nm^{-3} recommended for shaft power applications,[8,14] thereby indicating the need for further development of the gas conditioning system. Efforts are underway in this direction.

Water was extensively used in the gas conditioning system as the scrubbing medium. The effects of spraying this tar-laden water on two plant crops, sunflower and mustard, were investigated in some preliminary experiments over two seasons.[7] Phyto-toxicity tests conducted according to standard methods indicated that the effluent was not toxic to the crops at least in the short-term.[7] However, long-term residual analysis of the soil has yet to be attempted.

Finally, an economic analysis was also carried out for the above system. This involved comparing the costs of generating electricity using the generator when operating in the diesel-alone mode and in the dual-fuel mode. The latter cost needs to be less than the former for the gasifier system to be economically viable. The Levelised Annual Cost (LAC) technique was used for this analysis.[15] The mathematical details are given elsewhere.[10] Some of the major findings of this analysis are:

(a) The level of utilization of the gasifier very strongly influences its economic viability. Thus, for very low utilisation levels (<1000 h yr^{-1}), the gasifier system is not economical even for zero biomass cost at the existing (1991) diesel prices in India (Rs. 5.62/litre[16]).

(b) The economics were found to be only marginally in favour of the gasifier system for utilization levels exceeding 2500 h/year and for biomass costs less than Rs. 0.2 kg^{-1} (about \$7 $tonne^{-1}$). This implies that the gasifiers be used not as stand-by systems, but as stand-alone systems. However, in view of the very low energy prices charged to consumers in rural India (varying from

Rs. 0.045 kWh^{-1} for agriculture to Rs. 1.71 kWh^{-1} for industry[17]), this may not be a feasible proposition.

(c) One of the major findings of this analysis was the economic viability of gasifiers for direct heat applications such as in seed driers and other agro-based industries like fruit and food processing units. These now depend on furnace oil to meet their heat energy demands, which typically constitute about 90% of their total energy requirements. Moreover, these industries are usually situated in rural areas, where biomass fuels (in the form of agricultural residues, tree cuttings, etc.) are readily available. It is felt that gasifiers can have an important role to play in such industries. Further, the economics showed that at the existing (1991) furnace oil price of Rs. 5/litre, the energy cost of furnace oil was ~Rs. 1020 MWh^{-1} compared with Rs. 840 MWh^{-1} for the gasifier-powered system.[7] Thus, it is considered that at the present level of technological development, gasifiers are more suited for direct heat applications than for shaft power applications.

Further, larger scale units (100 kW electricity or 500 kW thermal) with potential uses in rice mills, tea estates, charcoal industry and other such industries where the utilisation level is expected to exceed 4000 h per year and with on-site availability of the biomass fuel are also attractive propositions. The present gasifier system provides an ideal basis for scaling-up to these levels.

5. CONCLUSIONS

From the data and analysis presented above, it is apparent that the use of agricultural residues like sugarcane leaves for decentralized electricity generation up to 12 kW can be technically feasible. However, further improvements in the gas conditioning unit are needed before this technology is ready for large-scale field testing for shaft power applications. The economics, however, are only marginally favourable under the present conditions and are strongly influenced by the level of utilisation of the gasifier. Thus, stand-by gasifier systems with low utilisation levels (< 1000 h annually) may not be feasible propositions. However, gasifiers appear to be well suited for direct heat applications such as in seed driers and agro-based industries.

Thus, it is felt that with the associated uncertainties in the supplies and prices of crude oil, gasifiers utilising a variety of agricultural residues (which are not being used presently) have a bright future, especially in the Third World countries.

Acknowledgements—The authors gratefully acknowledge the financial support from Ministry of Non-conventional Energy Sources (MNES), Government of India, New Delhi for this study.

REFERENCES

1. Appendix I: Petroleum Statistics, Department of Petroleum and Natural Gas, Ministry of Petroleum and Chemicals. *Urja* **30**, 27–30 (1991).
2. R. C. Fuloria, Future petroleum exploration in India. *Urja* **30**, 47–52 (1991).
3. Decline in crude output continues. *Times of India*, Bombay edition, p. 15 (29 February 1992).
4. R. M. Jorapur and A. K. Rajvanshi, Operating experience and economics of a 15 kVA genset–gasifier system running on loose sugarcane leaves, in *Recent Advances in Biomass Gasification and Combustion* (Edited by P. J. Paul and H. S. Mukunda), pp. 257–273. Interline, Bangalore (1993).
5. R. Ramachandran, Petroleum conservation. *Times of India*, Bombay edition, p. 20 (13 February 1992).
6. F. Zhiying, The progress of research work on gasification of agricultural residues in China, in *Proc. FAO Second Expert Consultation on Producer Gas Development in Asia and the Pacific Region* (Malaysia and Thailand), pp. 272–295. FAO Regional Office of Asia and Pacific, Bangkok (1983).
7. A. K. Rajvanshi and R. M. Jorapur, Design and development of 10–15 kW gasifier running on loose sugarcane leaves. Final Project Report submitted to Department of Non-conventional Energy Sources (DNES), New Delhi (1992).
8. T. B. Reed and A. Dias, *Handbook of Biomass Downdraft Gasifier Engine Systems*. Solar Energy Research Institute, Golden, CO (1988).
9. A. Kaupp, *Gasification of Rice Hulls—Theory and Practice*. GATE/GTZ, Germany (1984).
10. A. K. Rajvanshi and M. S. Joshi, Development and operational experience with topless wood gasifier running a 3.75 kW diesel engine pumpset. *Biomass* **19**, 47–56 (1989).
11. N. Coovattanachai, The feasibility of producer gas in electricity generation, in *Proc. The First International Producer Gas Conference* (Colombo, Sri Lanka), Paper No. 13. Beijer Institute, Stockholm (1982).
12. I. E. Cruz, Development of rice husk gas producer systems in the Philippines, in *Proc. FAO Second Expert Consultation on Producer Gas Development in Asia and the Pacific Region* (Malaysia and Thailand), pp. 195–231. FAO Regional Office of Asia and Pacific, Bangkok (1983).
13. A. Kaupp and J. R. Goss, *Small Scale Gas Producer–Engine Systems*. GATE/GTZ, Germany (1984).
14. *Qualifying Testing and Performance Evaluation of Biomass Gasifier–Engine Systems—Procedure and Methodology*. Government of India, Department of Non-conventional Energy Sources, Ministry of Energy, New Delhi in collaboration with Action Research

Centre on Biomass Gasification Technology and Utilization, Department of Mechanical Engineering, Indian Institute of Technology, Bombay (1992).

15. V. V. N. Kishore, Economics of wood gasifier systems for irrigation pumping. *Indian J. Agric. Econ.* **44,** 72–80 (1989).

16. *Teri Energy Data Directory and Yearbook* 1990–91, p. 290. Tata Energy Research Institute (TERI), New Delhi (1992).

17. *Teri Energy Data Directory and Yearbook* 1990–91, p. 293. Tata Energy Research Institute (TERI), New Delhi (1992).