Utilisation of sludge gas for power generation through aero gas turbines

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Abstract. Utilisation of sludge gas as a fuel for power generation in gas turbines is discussed. Such a scheme is likely to be very cost effective particularly when the gas turbines are derived from aircraft after their flying life is over. The development and preliminary trials of a demonstration plant in Bangalore, based on a Rolls Royce "Dart" turbo-prop engine were promising and are described here. It is estimated that with the present proposal it may be feasible to meet over 30% of the domestic consumption of electricity under favourable conditions.

Keywords. Renewable energy sources; biogas; gas-turbines; sludge gas.

1. Introduction

Sludge gas from municipal sewage treatment plants is a valuable by-product, containing a high proportion of methane (CH_4 , 53 to 68 %), which has a calorific value in the range 19.17 to 24.53 MJ/Nm³. Since the gas is not easily transportable, it is convenient to utilise it in the vicinity of the sewage treatment plants, which are generally located at the outskirts of towns and cities. One way to utilise this renewable source of energy is to use it as fuel for internal combustion engines for mechanical or electrical power generation. In the context of the present acute shortage of electrical power in certain areas, such a scheme would certainly be useful, particularly for standby power generation for peak demand times and for supplying industries which could be located in the vicinity of the treatment plants.

While the use of reciprocating gas engines for operation on sewage gas is well known, the present project uses gas turbines, the main advantage of which is that the capital cost would be considerably lower as compared to reciprocating engines, particularly if the turbines are derived from aero-engine applications, after their normal flying duty is completed. Such engines are available at a nominal cost within the country and can be modified to operate on gas. The other advantages of a gas turbine system are the ease of installation (*ie* light weight, low requirement of cooling water), modular maintenance, quick starting and reliable operation. They also have a high temperature exhaust which can be utilised for process heating, thereby increasing the overall thermal efficiency of the system.

As regards gas turbine engines which can be used, the turboprop engines are particularly suitable as direct shaft outputs at speeds comparable to that of the generator are available. Several Rolls Royce 'Dart' engines which power aircraft for Indian Airlines and Indian Air Force (IAF), as well as AI-20 engines which power the transport aircraft of IAF are potential candidates. The Dart engines may be suitable for generators of approximately 1 MW and the AI-20 for about 2.5 MW. A large number of AI-20 Series A

engines are presently surplus with IAF as technically life-expired engines. These engines are in running condition but not certified for aircraft use. They represent a potential of about 250 MW of generating capacity which can be harnessed in the manner described and thus save the country over Rs. 100 crores. It may be mentioned that the Dart engine is manufactured indigenously by Hindustan Aeronautics Limited (HAL). Further, there are plans for indigenous development and manufacture of an industrial gas turbine operating on a coal-based fuel. Such an engine could be easily adapted to operate on sludge gas also, and in view of its proposed advanced design features, the overall efficiency will be quite high. It is thus clear that a continuous supply of gas turbines will be available in the country for operation on sludge gas. These engines could also be operated in dual fuel mode (*ie*, Diesel + sludge gas or kerosene + sludge gas), to meet any operational requirements. A certain amount of R&D work is involved in converting such engines to operate successfully on sludge gas. Efforts in this direction are described below. This is followed by a discussion of the techno-economics of the proposed systems.

2. Sludge gas production

Sludge gas is a product of anaerobic fermentation of organic matter present in sewage. In a treatment plant the concentrated sewage sludge is placed in large closed chambers called digestors, for periods upto 4 weeks. During this time fermentation of the sludge takes place due to the action of naturally occurring methanogenic bacteria, which results in the formation of a gas rich in CH_4 and also containing carbon dioxide (CO_2), nitrogen (N_2) and a trace of hydrogen sulphide (H_2S). At the end of the digestion process, the slurry is stabilised (*ie* rendered pathogenically harmless) and can be dried to yield a valuable fertiliser. The gas generation rate and composition are influenced by a number of factors, physical as well as biochemical and are prone to seasonal as well as other fluctuations depending on plant operation. The important physical factors governing gas generation are the temperature of the slurry, diurnal temperature fluctuation, solid content, ratio of new to old slurry, etc. Other important factors are the pH and composition of the substrate and the microbial populations. Further details of investigations in respect of these factors may be found in Trevlyan (1975), Pai *et al* (1978).

An important practical consideration for gas availability at a sewage plant is the problem of gas leakage through hairline cracks invariably present in digester domes. Repair of cracked domes presents many problems and a complete solution is yet to be found. One method of overcoming the problem is to devise an evacuation system which continually sucks off the generated gas, which is then stored in a gas holder, thereby reducing the positive pressure differential in the digestors and hence the leakage. The practicality of such a system was first demonstrated by Pai *et al* (1978) which gave an encouraging turn to an otherwise hopeless situation.

For the present purpose of estimating the biogas potential, recourse is taken to average the yield rates obtained from literature and those based on experience. For a treatment plant with primary sedimentation process followed by anaerobic digestion, a very conservative figure is $9,500 \text{ Nm}^3/\text{day}$ (normal cubic metres per day) per million of population served by the plant. For an optimised plant it would be around $20,000 \text{ Nm}^3/\text{day}$ per million (Barber 1977). For an optimised plant with secondary treatment, the actual gas generation achieved in a plant in the US is about $34,000 \text{ Nm}^3/\text{day}$ per million. There is of course no reason why similar figures cannot be

achieved in India also where the climatic factors are generally favourable for this purpose. Several treatment plants already exist in the country and more are planned in view of increasing population concentrations at metropolitan cities and consequent pollution problems. It is interesting to estimate the energy availability from this renewable source, given the above variability in the generation rate, in addition to which the variation in CH₄ content has also to be considered. Based on measurements at a sewage plant in Bangalore, a range from 53.4 to 68.3% can be taken as representative of this. With these figures the range of energy availability per million of population served by the plant can be estimated (table 1). The thermal power feasible is in the range 2-10 MW per million population.

Table 1. Power and co-generation from gas turbine operating on sludge gas

	Units	Low	Medium	High
1. Gas properties				
i) Methane content	% vol, wet basis	53.4	62.5	68.3
ii) Lower calorific value	MJ/Nm ³	19.18	22.45	24.53
iii) Gas generation rate	Nm ³ /day/10 ⁶ pop	9,500 ^a	20,000 ^b	34,000 ^c
2. Thermal energy				
i) Energy available/day	GJ/day/10 ⁶ pop	182.1	449.2	833.9
ii) Continuous rating	MW(t)/10 ⁶ pop	2.1	5.2	9.7
iii) Diesel oil equivalent	k litres/annum	1,831	4,517	8,386
iv) Value of diesel equivalent ^d	Rs (lakhs)/annum	65.4	161.0	299.0
3. Electrical energy				
i) Gas turbine efficiency	%	15.0 ^e	16.9 ^f	22.0 ^g
ii) Conversion efficiency ^h	%	13.7	15.4	20.0
iii) Electrical energy	kWh(e)/day/10 ⁶ pop	6,929	19,207	46,320
iv) Power rating	MW	0.75	1.00	2.00
v) Daily operation time	h/day	9.2	19.2	23.7
4. Economics of power generation^j				
i) Capital cost per kW	Rs/kW	3,244	2,520	2,175
ii) Generation cost				
(gas free of cost)	Rs/kWh	0.40	0.18	0.18
iii) Generation cost (gas @ Rs 0.23/Nm ³)	Rs/kWh	0.72	0.42	0.33
iv) Pay-back period ⁱ	months	5.6	2.6	2.5
5. Waste heat recovery^k				
i) Heat recovery	MWh/day/10 ⁶ pop	27.76	76.11	127.97
ii) Steam generation	t/h	4.10	4.53	7.50
iii) Overall system efficiency	%	68.6	78.9	75.3
(iv) Pay-back period	months	18	8.1	8.1

^a Typical gas generation rates of some primary treatment plants without any optimisation of gas generation; ^b Expected values for properly managed primary treatment plants; ^c Typical value for a treatment plant with secondary treatment (Hyperion, LA, USA); ^d Calculated on the basis of diesel oil @ Rs 3.57 per litre; ^e Typical figure for a derated Dart-6 engine; ^f Typical figure for a derated Dart-7 engine; ^g Typical figure for a derated Ai-20 engine; ^h Assuming a gear box efficiency of 98% and alternator efficiency of 93%; ⁱ Pay-back period calculated only in terms of equivalent diesel fuel saved, assuming sludge gas is available free of charge; ^k assuming that the engine exhaust gases are cooled to 200 °C to generate saturated steam at 981 kPa (10 kg/cm² absolute). The pay-back period calculated on the basis of equivalent furnace oil, @ Rs 2.97 per litre, of the same heating value, *ie* assuming a boiler efficiency of 100%. Hence, these figures are conservative.

It is interesting to note that the variation of CH_4 content is accompanied by changes in the CO_2 and N_2 content of the gas. During the measurements referred to above, the CO_2 content varied between 28 and 32 % and the N_2 between 2 and 15 %. The H_2S content of the raw gas varied between 100 and 2000 ppm, but most of it was retained in the gas holder water seal. The H_2S content in the gas holder outlet was in the range 8 to 15 ppm only.

3. Modifications to aero-engine

The aero gas turbine engine is primarily designed for operation on a liquid fuel such as kerosene (Aircraft Turbine Fuel, ATF). In order to operate the engine on a gaseous fuel such as sludge gas, changes have to be made in the fuel injection and control system. Further, for operation on ground, certain sub-systems such as the oil cooler and the governor have to be modified. The R&D efforts in the present project with respect to a Rolls Royce "Dart" turbo prop engine are briefly described.

3.1 Development of gas injector

In the "Dart" engine, the fuel (kerosene) is injected into each of the seven combustion chambers through an atomizer, which sprays the fuel in small droplets in the form of a hollow cone. Figure 1 shows a schematic view of a combustion chamber. The fuel spray is introduced downstream of a swirler which imparts a strong swirl to a portion of the combustion air and creates a region of recirculating flow which helps in stabilising the flame in the primary combustion zone.

The objective of the present development was to devise a suitable injector nozzle for sludge gas which could be retrofitted with minimum changes to the combustion and ignition systems. The limitations were mainly that the injector should be introducible into the existing swirler hub. Since the calorific value of sludge gas is about half that of kerosene (on a mass basis), it follows that for the same thermal input, the mass flow is twice the value. Further since the density of gas is about 2 orders of magnitude less than that of the liquid, it is necessary to use as large a pipe as possible to keep down the pressure losses.

In order to test various gas injectors, a combustion test rig was set up at the Koramangala & Chellaghatta (K & C) valley sewage treatment plant. Here one of the combustion chambers of the Dart engine was set up with an independent supply of air and fuel (sludge gas) at essentially atmospheric pressure conditions. The basis of such testing is that the gas velocities through the combustor are kept at values corresponding to engine conditions. The performance of any injector which works well at atmospheric pressure conditions would be better under engine conditions where the inlet pressure and temperatures are higher. Several injector configurations were fabricated and tested in this rig. These included injectors with multiple radial holes, a single axial hole and a variable radial slit injector. The last-mentioned injector injects the gas in the form of a radial fan jet. The slit gap could be adjusted prior to insertion of the fuel gun into the chamber. The combustion chamber exit was provided with an array of 8 chromel-alumel thermocouples so that the temperature distribution at the exit could be determined. The array could be rotated about the combustor axis, to obtain additional data points. The combustor was fitted with the original igniter spark plug.

The injector geometry had an important influence on the combustion characteristics,

from the view of obtaining easy ignition, stable combustion and good temperature distribution at the combustor exit. A desirable temperature distribution at the exit is such as to result in the long life of the turbine. The area-averaged temperature traverse quality factor (πTQF), defined as $(T_{\text{peak}} - T_{\text{average}})/(\Delta T_{\text{combustor}})$ is a measure usually employed to characterise this feature; a low value being preferable. Amongst the injectors tested the radial-slit was found effective in obtaining good ignition and temperature traverse quality. The slit-width was found to influence the temperature quality factor quite significantly. A narrower slit-width resulted in better mixing and gave a lower πTQF at the expense of a higher pressure drop. Based on these considerations, a slit-width was chosen to give an acceptable πTQF and a pressure drop of about 44 kPa (6.4 psi), figure 1. The πTQF of this injector is shown in figure 2 for various values of the temperature rise through the combustor. Also shown are results obtained with the original simplex type atomiser with the combustor operating on ATF. These tests were done at the combustion laboratory of the National Aeronautical Laboratory (NAL), both at atmospheric pressure and at elevated pressures. It is evident that the πTQF obtained with the gas injector is significantly lower than with the original simplex atomiser. For instance, for a temperature rise of 550°C, the gas injector gave a πTQF of 0.31 compared to about 0.44 with the simplex one. From this point, one can expect a much longer turbine blade life while operating on sludge gas. Also, due to the non-luminous flame the flame tube temperature will be lower, leading to better combustor life.

Subsequently, gas injectors based on this design were fabricated and installed on the engine. A manifolding system was developed to ensure equal supply of gas to each of the seven combustors.

3.2. Development of dual fuel injector

The gas injector was further modified to permit operation in a dual fuel mode, *ie* gas and kerosene. This injector was initially developed in the combustion lab as an air-blast atomizer, and subsequently tested on the engine in single and dual fuel operation.

Figure 1. Schematic view of "Dart" combustion chamber with radial slit injector for sludge gas.

Figure 2. Temperature traverse quality factors (TTQF) for gas injection and ATF.

3.3. Accessories and instrumentation

Other modifications to the engine included the development of a digital RPM indicator, a water-cooled oil cooler and high energy ignition units. The digital RPM indicator, apart from indicating engine speed, functioned as an overspeed trip to shut off the sludge gas flow through a pneumatic system in case of turbine speed exceeding a preset value. The oil cooler was modified for operation with water as coolant, since for stationary application, the air flow is inadequate. For starting of the engine, two high energy ignition units operating on 220 V AC were developed in the pilot plant of the laboratory.

Other systems developed for operation of the engine were the starting system based on lead acid battery bank, LP fuel feed system for ATF, mechanical linkage system for operation of throttle, trimmer, hp cock, speed governor and gas valves, etc.

The instrumentation included panel instruments for indicating major engine variables such as RPM, compressor pressure, jet pipe temperature, torquemeter pressure, oil temperature etc.

4. Demonstration plant

A demonstration plant to investigate the operation of a Rolls Royce Dart turbo-prop engine on sludge gas has been set up at the K & C valley sewage treatment plant of the Bangalore Water Supply and Sewerage Board (BWSSB). This treatment plant has a capacity of 168 million litres per day and provides primary sewage treatment, namely sedimentation followed by digestion of the sludge. When this project was conceived in 1976, the treatment plant had no facilities for gas storage and the availability of the gas was negligible. Investigations indicated that though gas generation was present, most of the gas was leaking away through numerous cracks in the digester domes. A pilot gas holder of 28 m³ was set up and a blower installed to extract the gas from the digester and fill the gas holder. With this system it was possible to minimise the overpressure in the digester and hence the leakage. It was possible to collect substantial quantities of gas and the proposal to set up a demonstration plant was taken up.

The layout of the demonstration plant is shown in figure 3 and a general view in figure 4. It consists of a gas collection and holder system, a gas conditioning and compression system, a gas turbine engine and an operating system. The gas collection system consists of a gas blower unit 1.5 kW (2 HP) which extracts the gas from any or all of the four digestors and transfers it to the gas holder. The gas holder is of the conventional moving bell type with a capacity of 2266 m³ (figure 5). It stores the gas at a pressure of about 90 mm of water column. The gas conditioning system is a filter filled with material for absorbing hydrogen sulphide. Initially steel turnings are being used for this purpose. The gas compression system comprises a 2-stage sliding vane rotary compressor driven by a 90 kW increased-safety motor, an inter-cooler, oil separators, after-cooler and a cyclone. The gas turbine engine is as discussed above and coupled to a variable-pitch propeller for absorbing the power developed.

In the next phase, it is proposed to replace the propeller with a generator for electrical power generation. A gear box to match the propeller speed (1200 rpm) to the generator speed (1500 rpm) would also be required.

5. Engine operation and performance

The engine was initially operated on its normal fuel and with the original injectors, to establish the functioning of the various systems. Thereafter, one of the seven combustors was fitted with the gas injector described in §3.1 above, with the remaining ones retaining the liquid fuel injectors. The engine was operated in this mode to establish satisfactory ignition and combustion of the sludge gas within the engine. Subsequently, all the seven combustors were fitted with gas injectors and operation with sludge gas alone was attempted. For controlling the start-up of the engine, a by-pass was provided for the gas after the gas compressor, so that it flows back to the gas holder. The gas flow was also controlled by means of a gate valve upstream of the compressor inlet. It was found that the ignition, acceleration and running of the engine were smooth and easy even when operating purely on sludge gas. The running time was initially limited to a few minutes owing to the small size of the pilot gas holder. Subsequently, the larger gas holder of 2266 m³ capacity was constructed and commissioned. Also, the engine was retrofitted with dual fuel atomizers to permit simultaneous operation on gas and ATF. For operation in dual fuel mode, the engine was

Figure 3. Lay out of demonstration plant at K & C valley, Bangalore. 1. pilot gas holder; 2. cooling tower; 3. cooling water pump; 4. gas filter unit; 5. compressor shed; 6. gas compressor I stage; 7. gas compressor II stage; 8. motor, 125 H.P.; 9. I stage oil separator; 10. inter cooler; 11. II stage oil separator; 12. after cooler; 13. control shed; 14. starter and safety panel; 15. control panel; 16. kerosene fuel tank; 17. booster pump; 18. linkage platform; 19. engine stand; 20. Dart engine; 21. flame trap; 22. 6" pipe line; 23. 6" gate valve; 24. blow-off valve; 25. 4"-2½" reducing elbow; 26. 2" gate valve (gas by-pass); 27. 2" gate valve (main flow); 28. 2-way cock; 29. flame trap; 30. link rod (by-pass line); 31. link rod (main line); 32. main flow valve handle; 33. by-pass valve handle; 34. throttle lever; 35. RPM controller; 36. trimmer; 37. HP cock (kerosene); 38. LP cock (kerosene); 40. fuel filter; 41. return pipe 2"; 42. cooling water line 2"; 43. 2½" pipe line; 44. 2" gas by-pass line; 45. 1" kerosene feed pipe; 46. gas flow orificemeter; 47. 6" pipe; 48. 2½"-2" reducing collar; 49. 2" pipe line; 50. gas inlet from booster fan; 51. valve; 52. non-return valve; 53. gas blower; 54. flame trap; 55. water trap; 56. valve; 57. digester; 58. gas manifold; 59. gas venting valve; 60. HP cock (gas)

Figure 4. View of demonstration plant based on "Dart" engine.

Figure 5. View of 2266 m³ (80,000 cft) capacity gas holder.

started on sludge gas alone. Subsequently, ATF was introduced and the flow of both fuels progressively increased as desired. When the engine is to be operated on ATF alone, compressed air is used as the atomising agent and the same gas compressor is used.

The engine has been operated in the dual mode to estimate its performance. The shaft horsepower is estimated from the torque pressure indicator, which is related to the

engine torque through a calibration curve. To ascertain a suitable operating point for ground running, the engine has been operated at several speeds in its recommended cruise range (13,800 to 14,000 RPM). Figure 6 shows the engine performance when operating with ATF alone as well as in the dual fuel mode, at a speed of 14,200 RPM. Due to limitations in the gas flow rate of the installed gas compressor, the engine cannot at present be loaded fully when running on gas alone. Hence liquid fuel upto about 27% (in heat value) is injected to obtain sufficient loading in these tests. The figure shows the system efficiency and the gas temperature in the jet exhaust (JPT) plotted against the engine output. In estimating the system efficiency, the thermal energy of the fuels as well as the energy input into auxiliaries such as the gas compressor are included in the input. It is observed that efficiencies when operating on ATF as well as on gas/dual fuel mode are substantially the same. This confirms the efficient combustion of sludge gas in the engine. It is interesting to note that for any given output the jet pipe temperature with dual fuel or gas operation is lower than with ATF operation. This factor should help in achieving longer turbine life when operating on gas or in the dual fuel mode. The lower turbine outlet temperature can be partly explained on the basis of the increased mass flow through the turbine due to the lower calorific value of the gas compared to the liquid fuel, which results in a higher output. In effect, it represents the recovery of some of the work of compression of the sludge gas, as it expands through the turbine.

Figure 6. Engine performance for operation on sludge gas and ATF.

6. Techno-economic aspects

In order to make even a tentative estimate of the techno-economics of gas turbine systems operating on sludge gas, it is important to recognize the large variability in the processes concerned. These relate mainly to the generation of the sludge gas and the engine performance parameters. Thus two comparative evaluations are carried out: the first one (evaluation I) considers the lower and upper practical limits for gas generation and gas turbine efficiencies in order to get an idea of the range of power generation potential and costs; the second one (evaluation II), considers various engine and system options for an average gas generation situation. This evaluation helps in placing the various options in perspective and brings out the influence of sludge gas pricing policy on the overall economics. Comparison is made with a reciprocating engine system operating on diesel or sludge gas.

6.1 Evaluation 1

The electrical energy that can be generated depends on the efficiency and ratings of the gas turbines available. In the present context of using available aero-derivative engines, it is pertinent to examine the Rolls Royce Dart series 6 engines (which power Viscount and Fokker F-27 aircraft), the Dart 7-series which power the AVRO 748 aircraft and the AI-20 Series-A engines which are surplus with IAF. These engines will be operated at derated conditions in order to obtain a longer time between overhauls. The extent of derating will have to be obtained by conducting trials on demonstration plants. Section 3 of table 1 indicates the range of efficiencies which may be expected and the corresponding electrical outputs. The worst case corresponds to the Dart 6 operating with lean gas which gives an overall efficiency of just under 14%. The AI-20 engine operating with rich gas will give nearly 7 times this output at a system efficiency of around 20%.

To get an idea of the economics of the proposed scheme, three cases are evaluated, viz:

- A Dart 6 engine operating with lean gas;
- A Dart 7 engine operating with medium quality gas;
- An AI-20 engine operating with rich gas.

For comparison, a diesel gen-set is also evaluated. For estimation of the capital costs of the plant, the cost of a gas holder of 2266 m³, a gas compression unit, time-expired aero engine (1-working + 1-standby), an alternator, a gear box and civil engineering works are included. For estimation of the recurring costs, the cost of fuel (as indicated in the table), cost of consumables such as electricity for gas compression, lubricants, interest on capital, depreciation and operational maintenance at 18%, 5% and 2% per annum respectively, and overhauling costs for engine and staff costs are included. For purposes of the calculation, the plant is assumed to operate for 2700 hours per annum for the Dart 6 system and 6000 hours per annum for the Dart 7 and AI-20 systems.

The results are summarised in §4 of table 1. These are tentative figures since certain assumptions regarding cost and time between overhauls of the engines under the proposed operating conditions are not definitively known at present. It is seen that for gas-fuelled plants the capital costs are very low and decrease with increasing plant size and efficiency. Even for the worst case, the capital cost is about Rs. 3,244 per kW which is about half that of a comparable Diesel gen-set (Rs. 6300 per kW). The pay-back

period is based only on the equivalent diesel fuel saved, assuming sludge gas is available free of charge. As can be seen, the period is very short—less than 6 months for the worst case and less than 3 months for the best case. This is impressive by any standards. Of course, if one considers the pay-back in terms of revenue or production resulting from the electricity generated the results would be even more impressive.

The cost of generation per kWh is also found to be very low ranging from Rs. 0.40 for the worst case to Rs. 0.18 for the best one, assuming the gas to be available free of charge. This works out to between 23 % to 10 % of the cost by diesel generation (Rs. 1.75 per kWh) and compares with traditional methods of much larger unit size and higher capital costs. Even with a reasonable charge on the gas, the cost can be made very competitive as shown in table 1.

Finally, the significant improvement in plant efficiency as a result of adding a waste heat recovery system is indicated in §5 of table 1. As the efficiency of gas turbines, especially those of early vintage is rather low, the exhaust gases flow out at a high temperature of around 500°C which makes a strong case for waste heat extraction. Suitable heat exchangers for this application can be designed and fabricated indigenously. The heat can be recovered in the form of hot water or steam depending on requirement and application. The table shows that large amounts of steam can be generated and then the overall system efficiency would be around 69–79 %. The pay-back period, again on a very conservative basis, is very impressive, ranging from the worst case of 18 months to about 8 months for the best.

6.2 Evaluation 2

It is well known that the efficiency of simple cycle gas turbines is generally lower than that of reciprocating engines which have higher compression ratios. One technique to improve the efficiency of the gas turbine is to incorporate a heat exchanger between the turbine exhaust and the compressor outlet. Significant improvement in efficiency of the order of 50 % can be achieved with an additional heat exchanger and engine modifications. In the present evaluation the effects of attaching a heat exchanger, with an effective value of 0.8, to the engine system are considered.

Another important factor considered is the pricing of the sludge gas which will naturally influence the final economics. Three possibilities are considered, *viz*: —sludge gas is supplied free of charge; —gas is charged equivalent to coal on a heating value basis, say Rs. 0.23/Nm³; —gas is charged equivalent to Diesel oil on a heating value basis, say Rs. 2.21/Nm³.

For this evaluation, the costing has been done in the same manner as in evaluation 1 above. The cost of a heat exchanger is tentatively assumed as Rs. 1200 per kW. The plants are assumed to operate for 6000 hours per annum. The results are summarised in figures 7 and 8. They show that if the gas is assumed to be free or charged a nominal rate, the simple aero-engine systems are most cost-effective and have the lowest capital cost. For these cases the cost of power generation will be lower than that with a reciprocating gas engine. However, in case the gas is charged equivalent to high speed diesel oil, the picture alters considerably. The low efficiency of the simple cycle gas turbine results in a high fuel cost and hence high cost of generation. With the addition of the heat-exchanger, the cost of power generation can be very competitive with the reciprocating engine. The capital cost for the gas turbine with a heat exchanger will still be much lower than that of the reciprocating engine. For example, for the case of a

Figure 7. Cost of power generation from sludge gas. (exch.—exchanger; recip.—reciprocating)

Figure 8. Conversion efficiencies and capital cost of alternative systems. (exch.—exchanger; recip.—reciprocating)

AI-20 engine with a heat exchanger, the capital cost would be about Rs. 3700 per kW, compared to about Rs. 7800 for the reciprocating engine and the cost of generation would be about Rs. 1.50 in both cases.

7. Concluding remarks

In the present scenario of acute power shortage in several parts of the country the proposal to utilise aero-gas turbines appear quite attractive. Given favourable conditions it would be quite feasible to generate about 84.24 TJ (23.4 million kWh) per million of population served by a sewage plant, per annum. This compares with the national average for domestic consumption of electricity of 39.6 TJ (11 million kWh) per million population (1977–78 figures). This may not be a very fair comparison since it includes the rural population. Even for a developed city like Bangalore, the estimated per capita domestic consumption is 68 kWh per annum. Thus the potential for power generation through sludge gas for metropolitan areas is a significant 34 %.

Further, the cost effectiveness of using aero derivative gas turbines appears to be very attractive. The cost of power generation, even with the simple aero engines of early vintage can be low—18 to 23 paise per kWh. The capital cost per kW would be very low: in the range of Rs. 2175 to Rs. 3244 per kW. This is much lower than corresponding figures for diesel or gas engines (Rs. 6300 to Rs. 7814 per kW). Even if the gas is priced at a rate equivalent to high speed diesel, the gas turbine system can be made competitive by the addition of a heat exchanger system. Thus the techno-economics appear very favourable. Moreover, the proposal will permit the utilisation of a large number of time expired aero engines available in the country.

The tests with the demonstration plant set-up have indicated the basic practicability of the proposed system, in respect of engine modifications, operation and performance. Of course, further testing to demonstrate the endurance of the engine is still required. The indications of the combustor tests as well as the fortuitously low sulphur content of the gas (as a result of absorption in the gas holder), suggest that long life between overhauls should be possible. Thus there is every reason to pursue the proposal further by setting up actual generating plants wherever possible. Also every effort must be made to set up and optimise sewage treatment plants wherever necessary, in order to reduce pollution and to utilise the by-products such as sludge gas and fertilisers to the maximum extent possible.

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