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Hybrid Cogeneration System Fueled with Biogas Obtained from Urban Sewage Water

When treating urban waste water, a large quantity of sludge is produced. This sludge may by used in fermentation tanks to obtain biogas with medium to high levels of methane, which is ideal for electric energy and heat production. The aim of this paper is to develop a theoretical study regarding the use of biogas in power and heat generation modules. Biogas can be used for fueling internal combustion engines or fuel cells, which in turn generate electricity. Waste heat contained in the exhaust gas can be recovered in order to maximize efficiency. The theoretical study presented in this paper evaluates electrical and overall efficiency of a biogas production installation inside an urban waste water treatment.

Keywords: *biogas, cogeneration, gas engines, fuel cells, waste water*

1. Introduction

In present context, when oil prices hit all-times high values, diversification is a key element in the power generating field. Also, because of rising prices for fossil fuels, alternative fuel technologies are becoming more and more economically viable.

One such alternative fuel, biogas, can be produced by fermentation of organic waste, thus making use of materials which otherwise would be wasted. Urban waste water contains medium levels of organic material which makes it a good fuel production source. Biogas production is coupled with waste water treatment, a process necessary for complying with environmental law.

2. Biogas production

In the search for cost-effective levels of operation - with corresponding reductions in charges for waste water - the operators of treatment plants frequently optimize not only the actual process of waste water treatment but also the energy-related scope for recycling existing resources [1]. On top of this, they strive to reduce the volume of material that requires disposal and even process sludge into fertilizer products.

There are many opportunities for power generation (see figure 1). Cogeneration of heat and power (CHP) is one of the most effective and most widely used options, in which the heat and power is used in-house and/or sold [2].

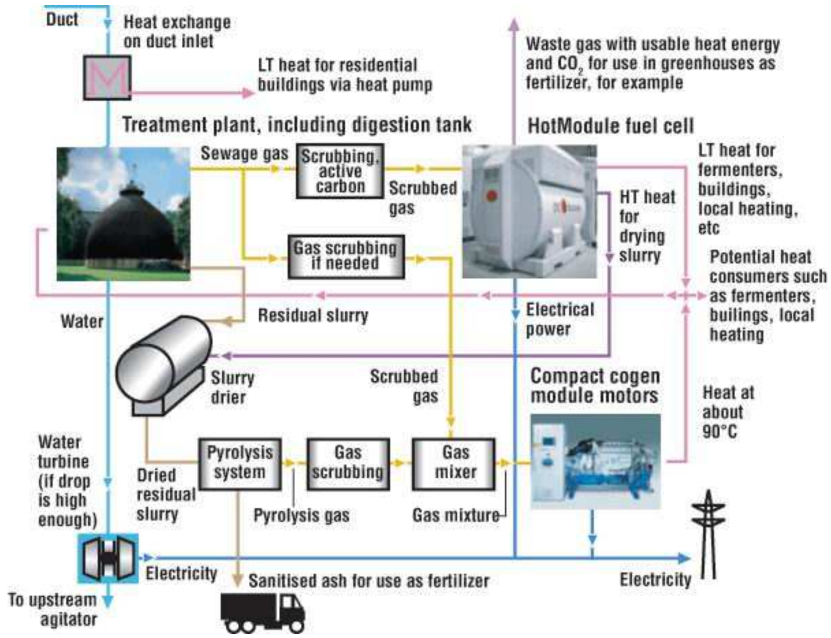

Figure 1. Schematic diagram for sewage plant with biogas production and use

Inside the treatment plant, the most important provider of power is biogas. This gas is created in the digestion tank by a fermenting process (see figure 2) and, depending on the source of waste water, has a methane content of 50%-85%. It is well suited to the operation of CHP. Every cubic meter of waste water yields roughly the amount of biogas required to produce 1 kWh of electricity plus 1 kWh of heat in a CHP operation.

3. Biogas operating strategies

In the classic case, a waste water treatment plant employs engine-driven compact cogeneration modules in a CHP application. Manufacturers offer suitable lean-burn engines that make effective use of biogas with methane content as low as 50%-65%.

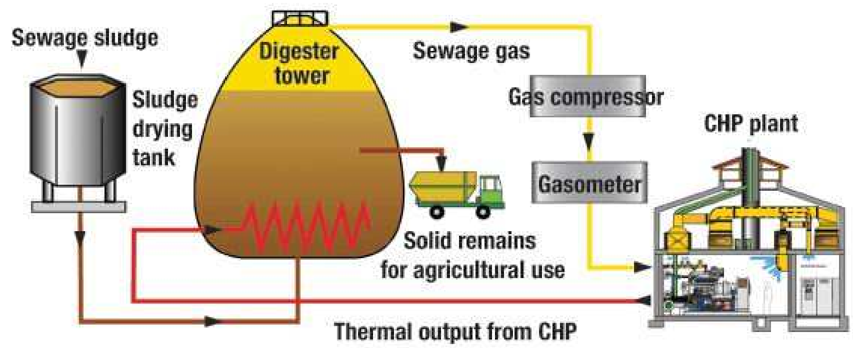

Figure 2. Schematic diagram for biogas production

Compact cogeneration modules of this kind are frequently employed that have power ratings of about 150 kW and above, provided that the treatment plant produces a sufficient volume of gas [3]. The principle of the lean-burn engine is to counteract the formation of pollutants during the combustion process. A closed loop control system such as oxygen-sensor, helps to achieve optimized combustion, even if the methane content fluctuates.

The high-temperature fuel cell is a modern version of the CHP approach [4]. It can be used as an alternative or an addition to the classic system. Devices such as molten carbonate fuel cells (MCFCs) process gases with a combustion value of about 3 kWh/m^3 and above. The MCFC can process natural gas or scrubbed biogas without any problems.

Typically, the volumes of biogas generated by medium-sized treatment plants are sufficient to allow the use of power-generating systems, and these can include a hybrid solution that combines a fuel cell compact cogeneration module with a classic gas engine cogeneration module. Such a system is able to bring together the strengths of both of these technologies (see Table 1).

A common feature of fuel cell and engine-driven classic compact cogeneration modules is their reduced output of CO_2 when compared with the separate generation of heat and power. Compared with the power generated in large coal-fired power stations and separate heat generation, CHP produces about one third less CO_2 per kilowatt hour of usable energy. The use of biogas as a primary energy source makes it possible to achieve CO_2-neutral energy conversion.

If gas is available in sufficient volumes, the characteristics of engine-driven and fuel cell operated compact cogeneration modules demonstrate the benefits of combining these two technologies.

Table 1.

Characteristics of the MCFC	Typical characteristics of engine-driven compact cogeneration modules
High level of net electrical efficiency – about 47% AC	Proven technology, long service life
Electrical efficiency rating in part-load operation is virtually identical to that in full-load operation	Good value for money
Relatively constant electrical efficiency rating, even if combustion value fluctuates	Responds flexibly to changes in gas combustion value
Use of high-temperature heat (about 400°C) is possible and economically beneficial	Can be controlled flexibly cross a power range of 50%-100% of nominal rating, can be started up and shut down frequently
Clean flue gas gives better waste air (SO_2 and NO_x levels are virtually zero, and CO output is 9 ppm)	The scrubbing of biogas is only required if the sulphur content is extremely high
The fuel cell stack is the only major part that ever requires scheduled replacement	Inexpensive overhaul and cost-effective replacement of all wearing components
Effective operation of absorption refrigeration machines is possible	High power-to-weight ratio
The service life of a fuel cell stack is 25000-30000 hours	Frequent maintenance intervals
Scrubbing of biogas is mandatory to eliminate sulphur and its compounds	Electrical efficiency of about 39%
As part of a hybrid system, it is best suited to base-load operation without extreme load changes and few start-ups and shutdowns	Electrical efficiency reduces during part-load operation
It is still substantially more expensive than comparable engine-driven CHP systems	Higher emissions than MCFC
Replacement of a fuel cell stack is expensive	Use of heat is cost-effective down to 90°C
Has a lower power-to-weight ratio than an engine-driven compact cogeneration module	

A hybrid system gives investors the opportunity to combine a proven technology that has good prospects with a new efficient energy converter. Such a system can serve all internal consumers in a waste water treatment plant and can generate surplus power that can be offered for sale on the open market.

An overall control system must be employed that integrates all of the closed loop control systems employed in the power generating facilities of the hybrid system. This is essential to make optimum use of the hybrid system. It must take into account the prevailing availability of biogas and the requirement for heat and power.

4. Discussions

CHP systems operating on biogas obtained through fermentation of urban sewage sludge present several characteristics depending on numerous factors [5]. Waste water flow has a major influence on such a biogas operated plant. Calculations for total biogas available energy values were done for different waste water flows discarded by a treatment plant with a medium treated water flow of 2000 l/s. Compared to waste water from the food industry, urban waste water has a lower content of organic matter. Given the fact that in order to comply with environmental law, not all of the waste water can be treated with anaerobic bacteria, only part of the waste water flow can be used for biogas production.

Apart from the waste water flow values, the actual energy available also depends on biogas quality (methane content, usually in the range of 50%-65% in the case of urban waste water treatment plants [6]). The following equation was used for calculating available energy values:

$$H_{av} = Q_{biogas} \cdot H_{biogas}, \quad (1)$$

where:

H_{av} – available energy [kW]

Q_{biogas} – biogas volumetric flow [m^3/s]

H_{biogas} – calorific power of biogas [kJ/m^3]

The production facility has an internal specific consumption of 0.184 kWh for every cubic meter of processed waste water, which lowers electrical efficiency (Figure 3). A smaller influence of biogas quality is observed in the case of the fuel cell module (Figures 4 and 5). The sharper drop in efficiency as methane content draws closer to lower values when operating an engine fueled with biogas [7], is explained by the increased heat loss due to larger burn angles (flame speed drops as the methane content is lower [8]).

Equation (2) was used for calculating internal consumption, while equations (3) and (4) for net electrical output and electrical efficiency:

$$P_c = 0.184 \cdot \frac{kWh}{m^3} \cdot Q_w, \qquad (2)$$

$$P = \eta_f \cdot H_{av} - P_c, \qquad (3)$$

$$\eta_e = \frac{P}{H_{av}}, \qquad (4)$$

where:
P_c – internal power consumption [kW]
Q_w – waste water flow [m^3/h]
P – net electrical power output [kW]
η_f – fuel cell module efficiency [-]
η_e – electrical efficiency, fuel cell module [-]

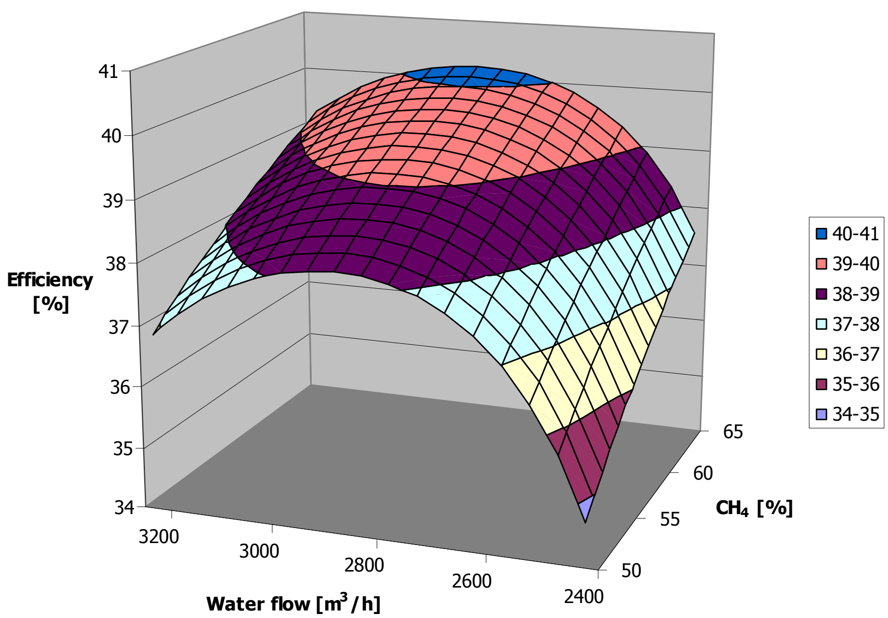

Figure 3. Electrical efficiency – Fuel cell module

Most of the heat released through the process of biogas combustion (in an internal combustion engine or inside a molten carbon fuel cell) is wasted when expelling exhaust gas into the atmosphere. Hence, the low efficiency values for this operating strategy. Heat contained in the exhaust gas can be recovered using a cogeneration of heat and power installation with overall efficiency up to 85%. Equations similar to (2), (3) and (4) were employed for calculating overall efficiency for a CHP operating strategy with engine-driven module (Figure 4) and fuel cell module (Figure 5). Efficiency levels are higher for fuel cell modules. The change in efficiency curve (Figure 6) is due to the fact that below a certain volume of biogas the engine-driven module has to be shutdown.

5. Conclusions

Urban waste water must be treated before being discarded into local rivers and other water sources. When using a two stage treatment process, with an anaerobic stage followed by an aerobic one, medium to high quality biogas can be obtained. Compared with other production methods, like gasification and fermentation of different organic material, methane content is high, up to 65%, even if specific production (cubic meters of biogas for a given volume of waste water treated) is lower.

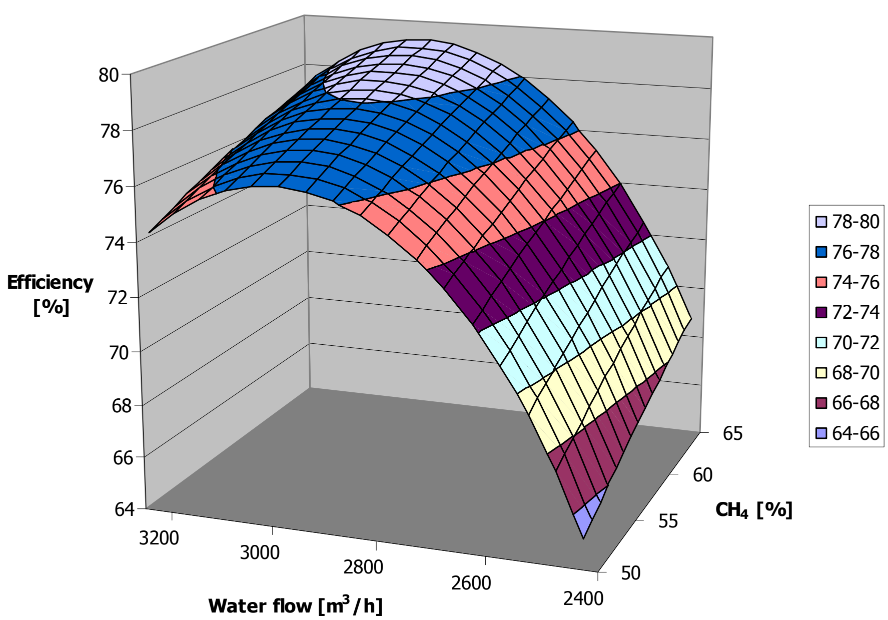

Figure 4. Cogeneration efficiency – engine-driven module

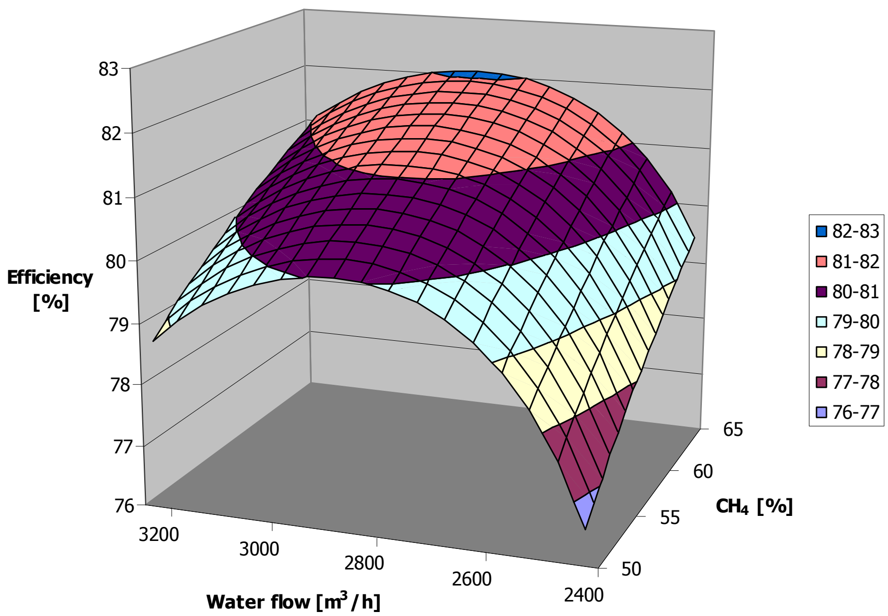

Figure 5. Cogeneration efficiency – fuel cell module

By using biogas to produce power and heat in a cogeneration scheme installation, high levels of efficiency can be achieved. When two units with roughly equivalent power ratings are combined, scope for closed loop control of 75%-100% can be achieved, assuming virtually constant volumes of waste water. However, if the volume of biogas requires a level of operation below the 75% mark, the power rating of the fuel cell can be restricted or, if necessary, the engine may need to be shut down.

Fuel cell and engine-driven compact cogeneration modules operate with reduced output of CO_2 compared to separate generation of heat and power. Compared to other biofuels, the use of biogas as a primary source makes it possible to achieve CO_2-neutral energy conversion. Operating a treatment plant (with medium waste water flow of 2000 l/s, even if not all the flow is used for biogas production) on biogas saves ca. 500 000 tones of CO_2 / year, an essential environmental benefit becoming ever more important as pollution levels keep rising.

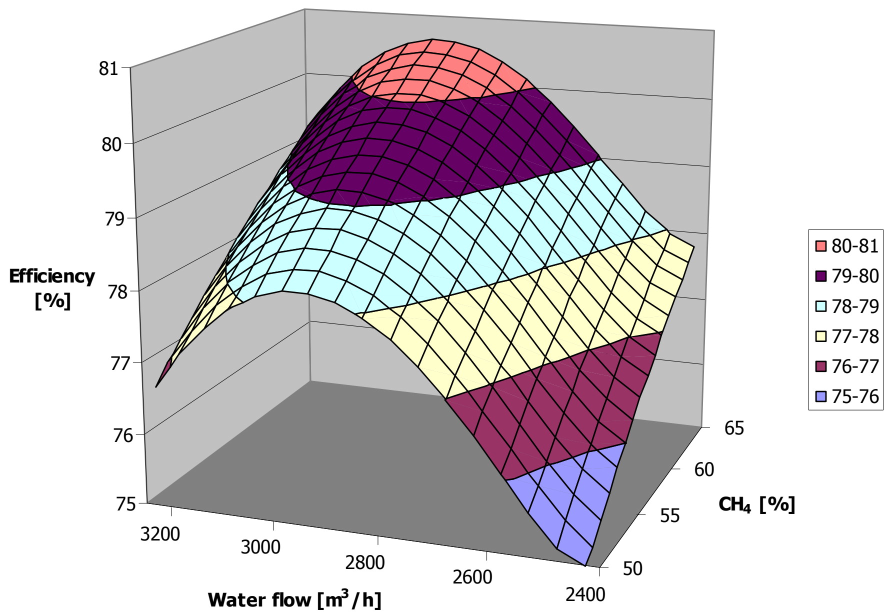

Figure 6. Cogeneration efficiency – fuel cell with engine hybrid system

From an economical point of view, implementation of this kind of projects requires substantially higher initial costs compared to classical treating facilities. One major issue is the gas scrubbing required in order to use the biogas in internal combustion engines but even more so for fuel cell modules. The main component that needs to be removed before the biogas is used is H_2S, a highly corrosive gas. Additional high costs arise when CO_2 needs to be removed in order to obtain a gas with very high levels of methane (up to 99,5%). However, taking into account rising prices for fossil fuels and inevitable high energy prices, alternative fuel technologies are becoming more and more economically competitive. Another factor which contributes to higher economical benefits is the option of green carbon credits trading, made possible by implementing this kind of technology. Given the rising price for natural gas, one option that will probably be exploited by more and more biogas producers is removing the CO_2 content and compressing it in order to obtain compressed natural gas (CNG), a biofuel with numerous advantages when used in vehicles equipped with spark ignition engines. However, even when employing new and high efficiency power production installations like molten carbonate fuel cells, these projects have a payback period of around 10 years.

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