TECHNICAL AND ECONOMIC ASPECTS OF THE OPERATION OF A CHP SET IN THE WASTE TREATMENT PLANT IN CZĘSTOCHOWA

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INTRODUCTION

The utilization of surpluses of waste gaseous fuels through their use for supplying power generator units or coupled heat and power generating sets driven by gas engines is one of the most rational methods of waste fuel utilization. In the case of high-methane fuels (such as natural gas, mine gas or biogas), this method is fairly widely used in modern industry. This is particularly advantageous in the case of biogas fuel with a zero gaining cost (i.e. from a waste treatment plant or a waste dump). For many years, a team of workers of the Institute of Internal Combustion Engines and Control Engineering of the Częstochowa University of Technology, under the guidance of Karol Cupiał, Prof. Sc. D. Eng., have been conducting studies on, and operating large stationary biogas engines [1]. The most recent of the biogas engines developed, tested and implemented to operation is the largest and most modern Polish engine 8A20G.

THE BIOGAS INSTALLATION AT THE CENTRAL WASTE TREATMENT PLANT IN CZĘSTOCHOWA

Since 1998, a co-generation source producing electric energy and heat has been operated at the Central Waste Treatment Plant in Częstochowa. This source is composed of a gas combustion engine driving an asynchronous generator, and a battery of two heat exchangers. The combustion engine is supplied with biogas fuel gained in the Waste Treatment Plant as a byproduct during the processing of sewage sludges. This is a typical coupled CHP (Cogeneration Heat & Power) power engineering installation generating electric energy and heat in the gaseous fuel source and at the site of demand (Fig.1).

The heat is delivered to the existing local heat distribution network. The generated electric energy meets, to a large extent, the power demand of the plant. CHP installations are characterized by a high degree of effectiveness. Owing to the fact that they are situated close to the user – most often, directly on his premises – the flow losses are substantially lower than for the central generation of electric power and heat. The applied co-generation set together with the existing system of three (two-fuel) water boilers satisfies the Waste Treatment Plant's heat demand in the form of heat process water necessary for heating up the sludge in three fermentation chambers during the whole year, as well as central heating water (during the heating season) and hot utility water (over the whole year).

Both the co-generation system and the water boilers are supplied with biogas gained in separated, closed fermentation chambers during methane fermentation which is the principal process of neutralization of organic sewage sludges. The advantage of the fermentation process is the fact that, in addition to sludge stabilization, it generates a combustible gas containing approx. 65% CH_4 and approx. 35% CO_2 (contributing to increasing antiknock resistance). Methane fermentation with gaining biogas is conducted in three closed fermentation chambers, from where the biogas is sent to a constant-pressure gas tank of a capacity of approx. 3,000 m^3. From the tank, through the plant's gas network, the biogas is delivered to the boiler house with 3 two-fuel (biogas or fuel oil) boilers or to the biogas power & heat generating set. The gas taken in is utilized chiefly for heating the fermentation sludge in five spiral-tube heat exchangers (process water – fermentation sludge) up to a temperature of 35-37 °C necessary for accomplishing mesophilic fermentation.

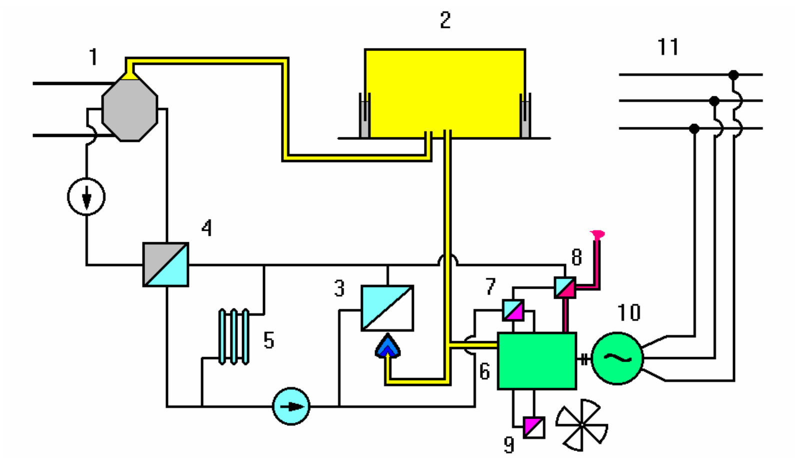

Fig. 1. Simplified schematic diagram of the connection of the heat & power generating set to the biogas, heat and electric installations of the WTP in Częstochowa: 1 – closed fermentation chambers, 2 – isobaric gas tank, 3 – gas boiler house, 4 – heat exchangers, process water-sludge, 5 – central heating of buildings, 6 – gas engine of the power generating set, 7 – heat exchanger, cooling fluid – process water, 8 – heat exchanger, combustion gas – process water, 9 – external standby cooler, 10 – asynchronous generator of the power generating set, 11 – 6.3 kV electric network

For the Polish climatic conditions this means that in the winter season the biogas production is only sufficient for heating the fermentation chambers. In the spring, summer and autumn seasons, a surplus of biogas occurs, which can be successfully used as a fuel for supplying the biogas heat & power generating set (Fig. 2).

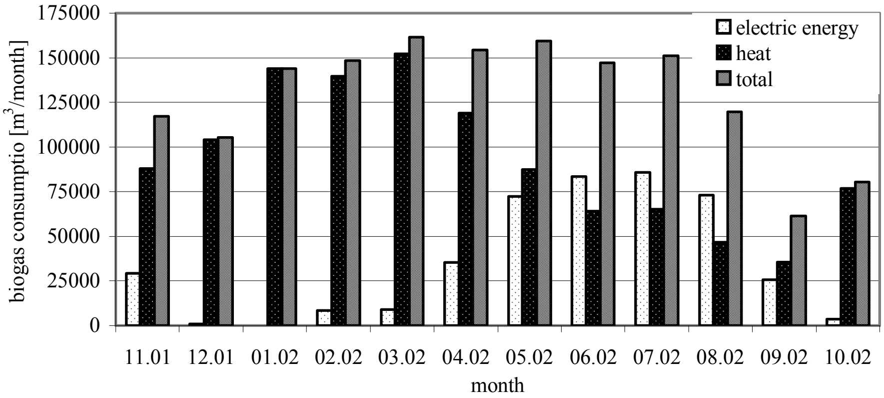

Fig. 2. The use of biogas for the production of heat in the boiler house and electric energy by the biogas power generating set at the WTP in Częstochowa in the period Nov. 2001 – Oct. 2002

The Częstochowa Waste Treatment Plant receives daily approx.75,000 m^3 of sewage, retains approx. 370 m^3 of sludge and produces up to 7,000 m^3 of biogas with a calorific value of approx. 22 MJ/m^3.

The average annual use of biogas in the WTP in Częstochowa is illustrated graphically in Fig. 3. Priority is given to process heat necessary for heating up the sludge in selected fermentation chambers.

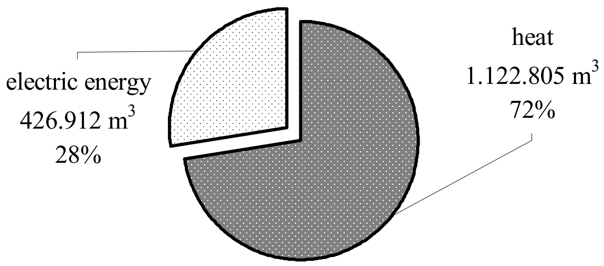

Fig. 3. The average annual structure of biogas use in the WTP in Częstochowa for the production of heat in the boiler house and electric energy by the power generating set

In the Częstochowa Waste Treatment Plant there is a large demand for process heat and heat for heating the Plant's buildings, and only about 30% of biogas is a surplus which can be used for the production of electric energy and heat in the co-generation unit with the biogas engine. This assures the generation of approx. 10% of electric energy purchased in a year from the Electric Power Station.

In waste treatment plants with a smaller heat demand, the biogas surplus can be larger; e.g. in Opole, about 1/3 of the total amount of biogas generated there was consumed in 2001 to meet process (boilers) demands [5].

THE HIGH-POWER BIOGAS ELECTRIC POWER & HEAT GENERATING SET

The 8A20G gas engine is a four-stroke, eight-cylinder in-line engine supercharged by a turbocompressor driven by a constant pressure-supplied internal combustion turbine [2, 3]. The piston stroke is 240 mm; the cylinder diameter is 200 mm; and the rotational speed is 1000 rpm. It has been designed based on a A20-type marine engine manufactured by HCP S.A. under the licence by SULZER. The engine has four-valve orifice-cooled heads. The outlet valves are made of Nimonic. The engine is supplied with biogas with the following average composition: CH_4 60-65 %; CO_2 30-34%; H_2 approx. 4%; N_2 approx. 2%. Also, small amounts of carbon monoxide, oxygen, hydrocarbons, hydrogen sulfide, ammonia and nitrogen oxide occur in the biogas. The carbon monoxide additive significantly increases the antiknock resistance of the gas, making it an attractive fuel for combustion engines. A schematic diagram of the 8A20G gas engine is shown in Fig. 4.

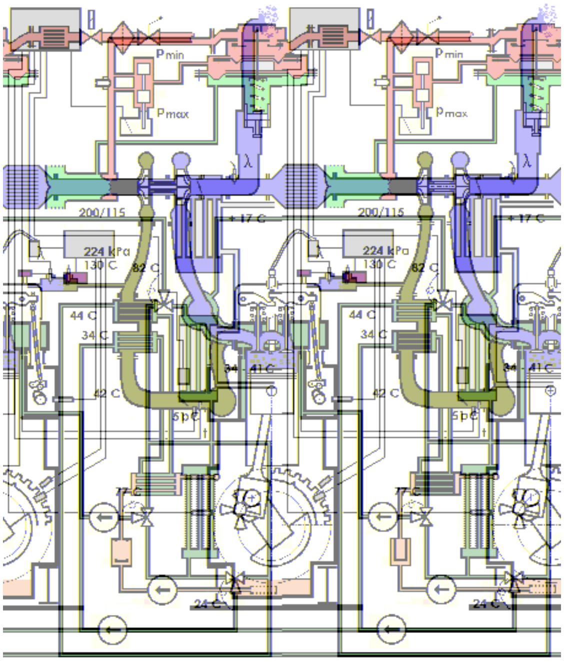

Fig. 4. Schematic diagram of the 8A20G biogas engine with a system of warm water–water and combustion gas–water heat exchangers

The gaseous fuel–air mixture is produced in a fixed-passage, low-pressure, zero-overpressure mixer situated at the inlet of a non-adjustable turbocompresor. After having been compressed to a pressure of about 1.3 bars, the mixture is cooled down to a temperature of approx. 40°C in a two-stage water cooler, from where it is delivered to the suction manifold and to the cylinders. The amount of mixture (and engine power) is regulated by a valve throttling the flow of the compressed mixture, situated between the mixture cooler and the suction manifold. The throttling valve is controlled by an electronic controller providing quantitative regulation.

The engine is furnished with a state-of-the-art air-fuel mixture regulation system incorporating a lambda probe. The signal from the lambda probe is passed to the controller, from where, by feedback, it acts on the current composition of the air-fuel mixture supplying the engine, thus additionally providing qualitative regulation. Additional signals correcting the air-fuel mixture composition come from pressure and temperature sensors installed in the engine head race. The controller software makes it possible to change controller characteristics and enables full real-time monitoring on a portable computer's screen. The ignition of the air-fuel mixture in the cylinders is accomplished by two-electrode sparking plugs power-supplied from individual ignition coils of a high-power digitally controlled ignition system. An IC 900 control module provides, among other things, the infinitively variable adjustment of ignition advance angle, the automatic selection of spark discharge energy, the adjustment of spark discharge duration and the automatic diagnostics of the ignition system.

The ignition system control module operates with an electronic knocking combustion detection and control system monitoring all engine cylinders. The automatic starting of the engine with compressed air delivered from a set of cylinders to the pneumatic starter mating with the toothed wheel rim of a flywheel is preceded by pre-purging of the suction and exhaust systems with clean air.

Blowing of the exhaust system with plenty of clean air, done prior to each starting and stopping of the engine, efficiently reduces the possibility of occurring an undesirable ignition of unburned air-fuel mixture in the exhaust system which incorporates additionally a combustion gas–water heat exchanger. A 6.3 kV asynchronous electric generator coupled with the gas engine operates in parallel with the national power grid. The generator operates at an over-synchronous rotational speed only slightly increasing as load increases (from 1,000 rpm for idle run up to 1,013 rpm for an engine power of 650 kW). The engine cooling system uses a warm water–water heat exchanger and a 6-fan cooler (outside the power station house) designed for carrying away to the environment of that heat surplus that cannot be taken by the Plant's heating installation. The combustion gas flows through an oxidation catalyst to the combustion gas–water heat exchanger and further on to the silencer & spark arrester located outside the biogas power station building.

The engine reaches the power of 650 kW and a maximum efficiency of 36.1%, which corresponds to an effective unit work of 1.26 MJ/m^3 and a unit biogas consumption of approx. 0.4 m^3/kWh. The active electric power of the set is 600 kW, and the generated electric energy is delivered to the 6.3 kV electric network. The system of warm water–water and combustion gas–water heat exchangers enables approx. 260 kW of heat from the engine cooling system and approx. 320 kW from the exhaust system to be recovered and delivered to the Plant's heating circuit, at an electric load of 600 kW. The operation of the biogas electric power & heat generating set is controlled by control & measuring systems and automatic safety systems cutting off the gas supply and arresting the engine. The engine combustion gas composition meets the requirements of TA-Luft.

OPERATIONAL EXPERIENCE

In the conditions of the Częstochowa Waste Treatment Plant, the biogas power generating set with the 8A20G engine is only operated in the periods of a biogas surplus occurence in the Waste Treatment Plant, that is from April to November. During this period, the set can be operated in a cycle of up to 14 operating hours/day, in total for about 2000 hours, with an average electric power of approx. 500 kW.

The monthly operation time of the power & heat generating set, as being currently operated at the WTP in Częstochowa, is illustrated graphically in Fig. 5, and the same one, broken into particular years of operation, is shown in Fig. 6.

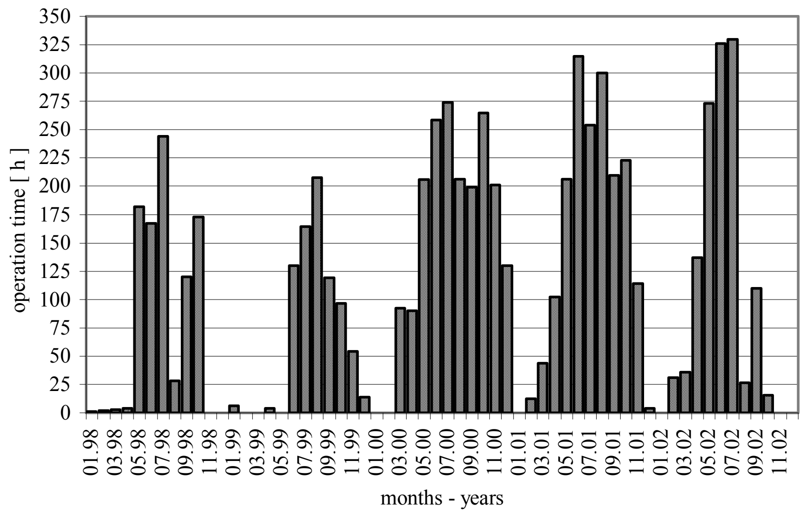

Fig. 5. Monthly operation time of the power generating set in the years 1998-2002

The operation in the first two years 1998-99 was conducted in a limited time, as research work was still carried out in those years. Practically, normal operation took place in the last three years, i.e. from 2000 to 2002. The operation time of the power generating set and the amount of energy generated during that time is shown in Figs. 6 and 7.

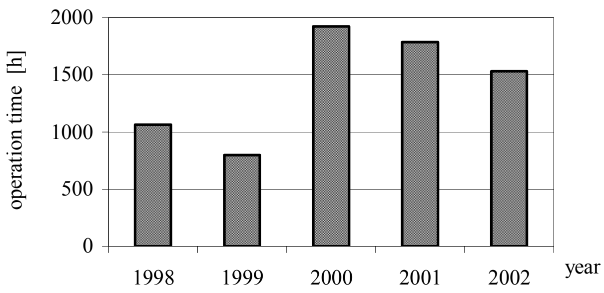

Fig. 6. Annual operation time of the power generating set in the Częstochowa Waste Treatment Plant

In 2002, the power generating set consumed totally 396.638 m^3 of biogas, which yielded a unit operational biogas consumption at a level of 0.548 m^3/kWh. For comparison, the measured unit consumption of biogas containing 65% CH_4 for the rated power amounts to approx. 0.4 m^3/kWh. This increase in unit biogas consumption is caused by the set operating at a lower load during loading and releasing of the power generating set and by a periodical decrease in the methane content of biogas.

Based on experience from the years 2000-02 it can be stated that an available biogas surplus allows the operation of the power generating set for at least 2000 hours per year. By reducing the heat consumption in the waste treatment plant, e.g. through decreasing the minimum temperature in the fermentation chambers to 32°C and by improving the thermal insulation of the fermentation chambers or increasing the efficiency of the process water–fermentation sludge heat exchangers, the operation time can be substantially increased.

The relatively high power of the set and the capability of storing the biogas in a high-capacity tank provide a possibility of utilizing the biogas surplus in the conditions of cyclic operation with a large share of electric energy generated in power peak load hours, which is economically very advantageous.

ECONOMIC EFFECTIVENESS OF THE CARRIED OUT PROJECT

The amount and value of generated electric energy and the profit of the Częstochowa Waste Treatment Plant gained in the years 1998-2002 from the operation of the biogas engine power generating set is shown graphically in Figures 7 and 8 (these data pertain to the production of electric energy only).

The unit price of the power generating set produced by H. CEGIELSKI-Poznań S.A. compares favorably with the unit prices of similar units of foreign make. The cost of 1kW of active power for this set is about USD 350, whereas, according to [4, 6], the unit cost of foreign sets of a similar power exceeds USD 500.

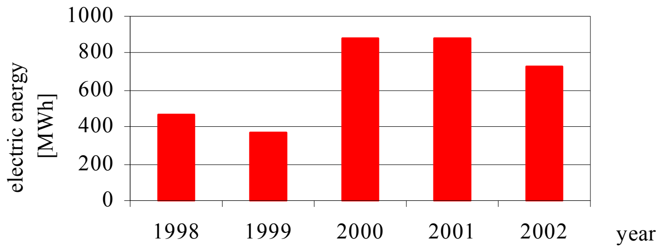

Fig. 7. Electric energy production by the power generating set operated in the Waste Treatment Plant in the years 1998-2002

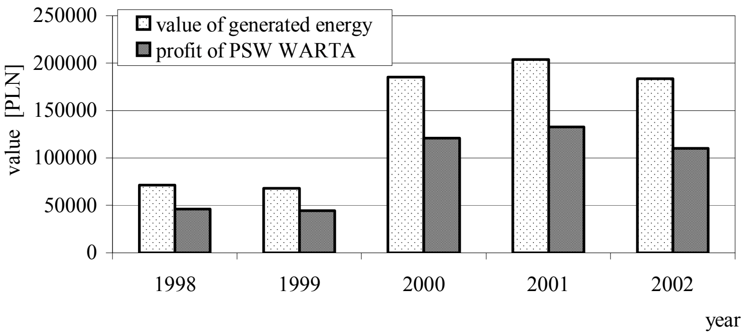

Fig. 8. Value of generated electric energy and the profit of the Częstochowa Waste Treatment Plant gained from the operation of the biogas power generating set in the years 1998-2002

The comparison of the operation costs of the power generating set driven by the 8A20G biogas engine and the cost of purchase of electric energy for industrial purposes is illustrated graphically in Fig.9.

It shows diverse costs of generation of 1 kWh of electric energy for successive years of operation of this power generating set, as calculated according to the level of prices effective at the end of December 2002:

– during a 10-year period of repayment of credit (contracted on preferential terms from the District Environmental Protection and Water Management Fund [7]) equal to the period of amortization of the power generating set;

– after the above period.

The current outlays include the costs of: engine service, operation, sparking plugs, and oil. The cost of biogas fuel – zero**.**

The purchase – on preferential terms – of a biogas power generating set and its operation in a waste treatment plant having a biogas surplus only periodically available is a profitable undertaking which is significant in the plant's energy balance [2, 3].

These effects are particularly significant after the expiry of the credit repayment and amortization periods, and this indicates that sets of high durability are especially economically attractive. For a biogas power & heat generating set, the unit costs of generation of 1 kWh of electric energy will make up, after the period of credit and interests repayment, only about 10% of the cost of purchase of electric energy from the Electric Power Station. Assuming the current level of prices, it can be expected that as early as after a period of 6 years of set operation, savings gained solely from the generated electric energy will be comparable to the cost of purchase of a new power generating set. Each time, an increase in electric energy purchase prices will have a significant effect on an increase of the economic effectiveness of biogas power generating set operation. The analysis of economic effects shows clearly that equipping a waste treatment plant with a gas power & heat generating set (as well as other plants having biogas available) is a fully economically justified undertaking.

A confirmation of the above is the fact that since its startup until the end of 2002 the heat & power generating set had operated (including a period of running-in and optimization tests – in total approx. 600 hours) 7,093 hours in the periods of occurring a biogas surplus, to produce 3,326.74 MWh of electric energy (with an average electric power of 0.469 MW) and approx. 2,860 MWh of heat, while consuming – under full load – about 0.4 m^3 of biogas on average for the generation of 1 kWh of electric energy. The value of electric energy generated during four years amounted to over PLN 712,000, this value being already comparable with the cost of this set.

The so far positive results of long-lasting operational tests of the 8A20G biogas engine driving the power generating set has proved that this is a reliable engine which is cheap in service and does not pose any operational difficulties. In waste treatment plants and at waste dumps that have a biogas surplus available, it can be a very valuable source of drive of a power generating set significantly contributing to an improvement in the plant's energy balance.

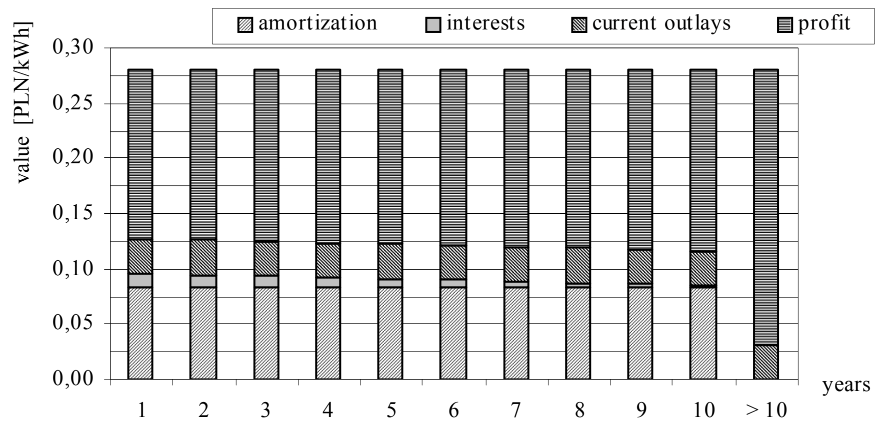

Fig. 9. Comparison of the cost of generation of 1kWh of electric energy by the biogas power generating set operated for 2000 hrs/year with the value of energy calculated based on its purchase cost = 0.28PLN/kWh (as per December 2002)

The average share of electric energy produced by the power generating set in the energy purchased from the Electric Power Station, as calculated for the years 2001-2002, amounted to approx. 9.90%, while in summer months reaching a value of 25% (Fig. 10).

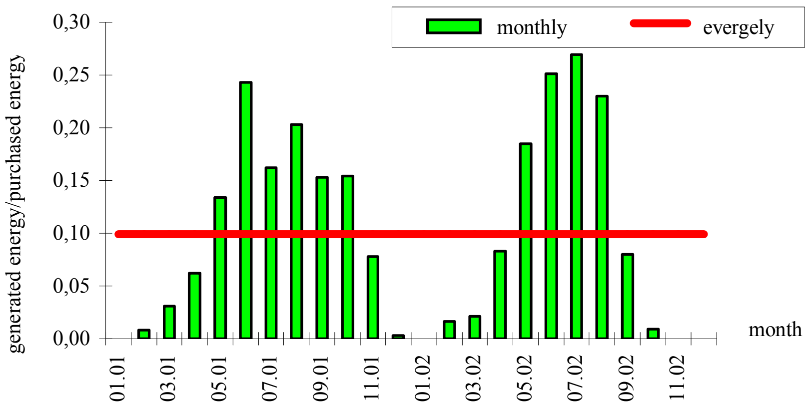

Fig. 10. Ratio of the amount of energy produced by the biogas power generating set to the amount of electric energy purchased by the Częstochowa Central Waster Treatment Plant from the Electric Power Station in the period from Jan. 2001 to Dec. 2002

The high economic effectiveness of the CHP set applied in the Częstochowa Waste Treatment Plant is a consequence of the fact that the analysis of economic effects does not burden the system with the costs of purchase of fuel (biogas) which, in a waste treatment plant, is a byproduct of the sewage sludge fermentation process.

CONCLUSIONS

– Biogas recovered in a waste treatment plant as a byproduct during sewage sludge fermentation is a valuable fuel which can be effectively utilized at the site of its recovery for supplying heat & power generating sets driven by gas engines.

– A particularly economically effective method of utilizing biogas is the co-generation of electric energy and heat.

The use of biogas heat & power generating sets in waste treatment plants is a recommendable pro-ecological activity, as it allows the elimination of methane emission to the atmosphere and enables significant economical benefits to be achieved.

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SUMMARY

Since 1998, a co-generation source producing electric energy and heat has been operated at the Central Waste Treatment Plant in Częstochowa. The combustion engine is supplied with biogas fuel gained in the Waste Treatment Plant as a byproduct during the processing of sewage sludges. This is a typical coupled CHP (Cogeneration Heat & Power) power engineering installation generating electric energy and heat in the gaseous fuel source and at the site of demand.

In the conditions of the Częstochowa Waste Treatment Plant, the biogas power generating set with the 8A20G engine is only operated in the periods of occurring a biogas surplus in the Waste Treatment Plant, that is from April to November. During this period, the set can be operated in a cycle of up to 14 operating hours/day, in total for about 2000 hours, with an average electric power of approx. 500 kW.

The relatively high power of the set and the capability of storing the biogas in a high-capacity tank provide a possibility of utilizing the biogas surplus in the conditions of cyclic operation with a large share of electric energy generated in power peak load hours, which is economically very advantageous.

The high economic effectiveness of the CHP set applied in the Częstochowa Waste Treatment Plant is a consequence of the fact that the analysis of economic effects does not burden the system with the costs of purchase of fuel (biogas) which, in a waste treatment plant, is a byproduct of the sewage sludge fermentation process.