ANALYSIS OF THE ACTUAL TECHNICAL AND OPERATIONAL PARAMETERS OF GAS COGENERATION SETS WITH COMBUSTION ENGINES

Adam Dużyński

Czestochowa University of Technology,
Institute of Internal Combustion Engines and Control Engineering
Armii Krajowej Av. 21, 42-201 Częstochowa, Poland
tel./fax: +48 34 3250501
e-mail: duzynski@imtits.pcz.czest.pl

Abstract

The present paper is the result of the author's research project no. 4 T12D 030 28 on the "Analysis of the actual technical and operational parameters of gas CHP sets" carried out by him in the years 2005-08, and financed by the Ministry of Science and Informatization in Warsaw. The primary scientific objective of the Project was to establish, compare and analyze the actual values of basic technical, operational and economic parameters for different CHP (Combined Heat and Power) sets driven by gas piston engines, operated in Poland. An analysis of the techniques of fuel gas utilization in piston engine-driven cogeneration sets, being currently used (and also likely to be used in the future), finding their application in combined energy management, has been made within the Project, and a review of the operational conditions of a dozen or so CHP sets operated in Poland, fed by biogas, mine gas from hard coal mine demethanization has been carried out. The results of this analysis have been included in the present monograph which, in addition to the review of the conditions of CHP set operation, provides conclusions that have also utility importance, and therefore can well be useful in making the optimal design of a combined energy system consisting of combustion heat- and power-generating sets.

Keywords: *CHP – combined heat and power, gas cogeneration sets, combustion engines*

1. The origin of the research project

Poland is one of the countries that have signed an international convention which pledges the signatories to reduce the emissions of greenhouse gases (CO, NO_x), and provides for attaining in the years 2008-12 a greenhouse gas emission volume not exceeding 94% of the emission volume of 1988. One of the means serving this goal – reducing the consumption of primary fuels – is the Decision of the Parliament (Sejm) of the Republic of Poland, which passed a resolution on July 8, 1999, on the increasing of the use of energy from renewable sources (MN No. 25, Item 365), and subsequently adopted it on August 23, 2001. The Resolution provides for increasing the share of "green" energy in Poland's overall energy balance up to a level of 7.5% in 2010 and 14% in 2020. In this context, the role of the energy use of renewable gas fuels, notably waste treatment biogas, landfill gas, or mine gas from colliery demethanization, is gaining priority importance, the more so because the Directive of the Council of Europe no. 1999/31/EC of 26 April, 1999, with the annexes hereto, imposes the obligation to degasify landfills. In addition, the Regulation of the Minister of the Economy and Labour of 12 September, 2004, on the detailed scope of the obligation to purchase electrical energy and heat generated from renewable energy sources (DzU No. 267, Item 2655) imposes the obligation to purchase green energy. As a consequence of the above, in Poland and other European countries alike, the years ending the past century saw a significant increase in the number of installed coupled decentralized electricity and heat generation systems operating with the use of internal combustion engines supplied with various gaseous fuels.

Cogeneration can be defined [5, 6] as the technological process of conversion of the chemical energy of primary fuels, e.g. gaseous fuels, into useful energy carriers, such as electrical energy, heat and refrigeration, which is accomplished in a single device or a group of interconnected devices (a system). If all the three above-mentioned energy carriers (and especially refrigeration) are generated simultaneously, the process is called trigeneration. The cogeneration of electrical energy and heat (or refrigeration), as accomplished using gas combustion engines, means not only a high CHP system efficiency of approx. 90%, compared to conventional heat and power generating plants, but also, which is now very important, a significant reduction of CO_2 emission as against the conventional heat and power generating plants. The production of electrical energy and heat (as well as refrigeration) in the cogeneration system should be evaluated very high because of very important ecological and social benefits ensuring the protection of the human natural environment. Indeed, cogeneration is one of the most favourable and highly efficient methods of reducing the atmospheric emission of CO_2, being regarded as one of the causes of the greenhouse effect, which is in this case running at a level much lower compared to coal-fired heat and power generating plants. Using gas cogeneration systems, both the emission indicators (due to the use of gaseous fuels) and the consumption of the chemical energy of fuels (owing to the use of coupled energy management) are reduced.

When comparing the indices of CO_2 emission of coal-fired power plants with those of gas piston engine power plants it turns out that the latter are even two times lower than the former. According to reference [6], for the combustion of natural gas GZ50 containing, among others, 97.8% CH_4 and having a calorific value of W_d = 35.9 MJ/m_n^3, the CO_2 emission index is 56 kg/GJ of combusted fuel energy (with total and complete combustion). For an engine efficiency of approx. 35%, the CO_2 emission is achieved at a level of 576 kg CO_2/1 MWh of generated electrical energy, whereas this index for coal-fired power plants averages out at approx. 990 kg CO_2/1 MWh [6]. The fuel chemical energy savings achieved from the coupling of the processes of electrical energy and heat generation is defined by the fuel energy savings ratio (FESR) which, for modern gas cogeneration sets, attains a value of (20-40)% [6].

The system of support for the producers of electrical energy from renewable energy sources (RES) and in cogeneration systems, based on negotiable Certificates of Origin, was established in Poland in the years 2005-2007 [4]. This was resulted directly from the need for adapting the regulations of the Polish law to the regulations in force in the EU. With respect to electrical energy from RES, Poland had to adjust its regulations to the provisions of the Directive 77/2001/EC. The Directive specifies the share of RES electrical energy in the overall energy consumption in particular member states, and imposes the obligation to implement the system of so called "Certificates of Origin", with the aim of supporting the development of renewable power engineering. A similar mechanism was employed in the so called "cogeneration Directive" of 2004 (EC Directive 2004/8/WE) promoting the generation of electrical energy in conjunction with the generation of heat.

The current model of supporting the producers of RES electrical energy was formed in March, 2005, while the system promoting cogeneration sources was put in place in 2007 along with the entry into force of the subsequent amendments of the Energy Law and the Environmental Law implementing the provisions of the above-mentioned Directives. Green energy is being sold on normal principles, and so called Certificates of Origin confirming the nature of generated energy are subject to trading at Towarowa Giełda Energii (Commodity Energy Exchange) S.A. The Property Rights Market (PRM) to Certificates of Origin for RES generated electrical energy (PMOZE and POMOZE_A) has been functioning since Dec. 28, 2005. It provides the basis for the established in Poland system of support for producers using renewable energy sources. On Dec. 28, 2005, trading in two additional types of property rights (PMGM and PMEC) to Certificates of Origin for electrical energy produced by high-efficiency cogeneration was also started within the PRM. Participation in the PRM enables the RES and cogeneration electrical energy producers to advantageously sell their property rights in so called Certificates of Origin confirming the nature

of generated energy, and the energy companies obliged to purchase those rights - to discharge of the obligation placed upon them by demonstrating the required number of Certificates of Origin. On July 1, 2007, TGE S.A., as an entity trading in property rights, initiated the Register of Certificates of Origin (RCO) providing the confirmation of electrical energy generated by high-efficiency cogeneration.

At present, 4 types of property rights to Certificates of Origin are recorded in the Register of Certificates of Origin maintained by TGE S.A. [4], whose balance as per Dec. 31, 2009, is summarized in Tab. 1 [4]:

- PMOZE - property rights to Certificates of Origin for RES generated electrical energy, whose production period, as stated in the Certificate of Origin, started from Feb. 28, 2009,
- PMOZE_A - property rights to Certificates of Origin for RES generated electrical energy, whose production period, as stated in the Certificate of Origin, started from March 1, 2009,
- PMGM - property rights to Certificates of Origin for electrical energy produced by cogeneration fired with gaseous fuels or with a total installed electric power of up to 1 WM,
- PMEC - property rights to Certificates of Origin for electrical energy produced in other cogeneration units.

Tab. 1. Balance of property rights in the Record of Certificates of Origin (RŚP) maintained by the Commodity Energy Exchange (TGE S.A.), as per Dec.31, 2009 [4]

PMOZE	
Submitted property rights [kWh]	18 978 106 036
Redeemed property rights [kWh]	17 988 988 641
Number of RCO members	1113
PMOZE-A	
Submitted property rights [kWh]	5 103 348 026
Redeemed property rights [kWh]	2 440 348 589
Number of RCO members	1113
PMGM	
Submitted property rights [kWh]	4 556 899 582
Redeemed property rights [kWh]	2 653 423 410
Number of RCO members	167
PMEC	
Submitted property rights [kWh]	41 430 488 632
Redeemed property rights [kWh]	29 982 485 236
Number of RCO members	175

The Property Rights Market system functioning in Poland enables energy enterprises to discharge of the obligation to obtain cogeneration Certificates of Origin and submit them to the Chairman of the Energy Office to be redeemed, which has been imposed upon them under the

Energy Law. In the second half of 2007, the enterprises were obliged to purchase 0.5% - for cogeneration supplied with gas or with a power less than 1 WM, and 16.5% for other cogeneration types. In 2012, this will be, respectively, 3.5 and 23.2%.

In Poland, similarly as in other countries, an increasing supply of gaseous fuels can be noticed, which results from the environmental protection requirements preferring the processes of digestion of fluid (municipal sewage) and solid (landfills) organic waste resulting in the formation of various types of biogas containing from 40 to 70% of methane. A considerable number of CHP sets already installed and operated in Poland – with significant economic and ecologic benefits – indicates that numerous new start-ups can be expected in the future. The confirmation of this fact are the data presented on the latest available in Poland map entitled "Energia odnawialna POLSKA 2006 – Zasoby i wykorzystanie" ("Renewable energy, POLAND 2006 – Resources and their use") published by the GEA Publishers, which provides information, among others, on gas cogeneration sets operated in Poland (together with their powers) and on the location and volumes of gaseous fuel resources (waste treatment plants, landfills, agricultural biogas plants) possible to be utilized.

An important factor increasing demand for such sets is the new Energy Law and the Regulation of Minister of the Economy on the obligation to purchase electrical energy and heat from unconventional sources. Therefore, it is essential to ensure that their future operators have access to credible and reasonably up-to-date information on the capabilities of such sets and on the problems associated with their operation.

In spite of the considerable spread of gas CHP sets with piston engines in Poland, there has been no scientific study so far, which would take into account the experiences of numerous operators of these sets and enable the actual technical and economic parameters, attainable in their different applications, to be reliably evaluated; and the available information indicated that the actual values often substantially deviated from the parameters published in brochures and offers.

The available literature, unfortunately limited, e.g. [5, 6], though containing some detailed data useful to specialists, provides practically no actual operational data for modern gas cogeneration sets, nor even refers to any sources of such data or indicates a ready-made tool that would be suitable for making a fast, unassisted, and reliable analysis of effect under Poland-specific conditions. In particular, there has been no information on the actual durability and the failure rate of gas engines, as well as on the influence of the latter on the overall cost of operation of a set (the costs of parts, repairs, and shutdowns).

2. The scope of the research project

Within the framework of Project no. 4 T12D 030 28 "Analysis of the actual technical and operational parameters of gas CHP sets" carried out by the author in the years 2005-2008, and financed by the Ministry of Science and Informatization, a comprehensive analysis of the following was made:

- the currently used (and also likely to be implemented in the future) techniques for utilizing gaseous fuels in piston engine-driven cogeneration sets finding their application in combined energy management;
- the actual operational conditions for a dozen or so gas CHP sets operated in Poland with piston engines supplied with biogas and mine gas from hard coal mine demethanization; and
- the operation & maintenance experience gained so far by their users.

The work contains unique, extensive data concerning the actual conditions of operation of a dozen or so cogeneration set operated in Poland, as detailed in Tab. 2, which have been collected by the users during the operation of those sets so far.

The results of the Research Project is the monograph "Analysis of the actual technical and operational parameters of gas CHP sets" [2] which, in addition to the examination of the conditions of CHP set operation, provides conclusions that have also practical importance, and

therefore can well be useful in making the optimal design of a combined energy system consisting of combustion heat- and power-generating sets.

Tab. 2. List of gas cogeneration sets covered by analysis within the Research Project carried out [2]

No.	Installation site	Engine type	Electric power [kW]	Thermal power [kW]	Start-up date
1	KAPUŚCISKA Waste Treatment Plant in Bydgoszcz	GE JENBACHER JMS 212 GS-B.L	511	540	08.2005
2			511	540	
3	JANÓWEK Waste Treatment Plant of Wroclaw	GE JENBACHER JMS 312 GS-B.LC	601	738	08.2001
4			601	738	
5			601	738	
6	Group Waste Treatment Plant in Łódź	DEUTZ TBG 620 V12K	933	1165	05.2004
7			933	1165	
8			933	1165	
9	Waste Treatment Plant in Brzeg	MAN E 2876 TE 302	100	164	12.2007
10			100	164	
11			100	164	
12	WARTA S.A. Waste Treatment Plant in Czestochowa	H. CEGIELSKI-Poznań 8A20G	600	550	12.1998
13	The collieries of Jastrzębska Spółka Węglowa S.A. in Jastrzębie Zdrój: - KWK KRUPIŃSKI - KWK PNIÓWEK - KWK BORYNIA	DEUTZ TBG 632 V16	3000	3400	12.1997
14		DEUTZ TCG 2032 V16	3900	4200	07.2005
15		DEUTZ TBG 632 V16	3200	3700	06.2000
16		DEUTZ TBG 632 V16	3200	3700	06.2000
17		DEUTZ TCG 2032 V16	3900	4300	12.2006
18		GE JENBACHER JMS 612 GS-S.LC	1819	1860	Test start-up II Q. 2008

Fig. 1. The title page of the monograph "Analysis of the act ual technical and operational parameters of gas cogeneration sets"

The monograph [2] presents the following, among others:

- types of gaseous fuels possible to be used in CHP sets;
- basic gas CHP sets (a CHP set with a piston engine fed with waste treatment plant biogas, landfill gas, coal-mine demethanization gas, agricultural biogas, and waste pyrolysis gas);
- basic energy indices of cogeneration sets;
- a comprehensive analysis of the actual technical & operational parameters of a dozen or so selected modern gas cogeneration sets successfully operated in Poland, including: technical descriptions of these CHP sets (the internal combustion engine, the installation for obtaining gaseous fuel and feeding it to the gas engines, the lubricating oil system, the combustion gas exhaust system, the generator, the heating water and emergency heat dissipation system, the ventilation system, maintenance activities (the schedule, scope, failures), the composition and operational consumption of gaseous fuel, the operational consumption of lubricating oil, combustion gas composition, the level of noise emitted by the CHP set, momentary CHP set operation parameters, CHP set operation time and its use, the generation of electrical energy and heat, the electric and thermal load of the CHP set, the electrical energy and heat balance, and the economic effects.

The completion of the Research Project and compilation of the monograph were possible thanks to the courtesy of the Boards of the companies operating the gas CHP sets shown in Tab. 2, as well as through personal contacts established by the author during eight International Scientific Conferences on Gas Engines – Design – Tests – Operation – Renewable Fuels organized by him, which were attended by a large circle of domestic gas CHP set operators, as well as the world's leading CHP set manufacturers, including Deutz Power Systems GmbH&Co. KG, GE Jenbacher GmbH&Co. OGH, MAN Nutzfahrzeuge AG, B&W Holeby, H. Cegielski-Poznań S.A., Wärtsilä Power Plants, ZMiN Wola of Warsaw, and the manufacturers of CHP set components, such as ABB, Enserv, ESSO AG, Motortech GmbH, TOTAL Lubricants, Woodward Governor Co.

When visiting the described plants, the author of the monograph made himself numerous verifying measurements of the parameters of those cogeneration sets, and performed an extensive and in-depth analysis of their operation hitherto; and in addition, what is very important, he also assessed the economic effects that had been achieved from their operation. An undoubted facilitation in obtaining permission for the author's access to respective industrial gas installations and to carry out measurements on those installations was provided by the obtained by him licences for taking such measurements in the form of permanent-validity qualification certificates in the supervision, operation and maintenance of gas, thermal and electrical equipment, including gas internal combustion engines without power limits, and the fact that he has specialized in the field of gas engines for about 30 years. The author has made a substantial contribution to the research on gas engines conducted by the IMTiTS (Institute of Internal Combustion Engines and Control Engineering), and in particular in the completion of the Scientific Research Committee target project no. 9 T12D 003 95C/2587 on "The prototype and optimization study of the heat-recovery 8AL20G gas engine-driven generating set and its implementation to series production at H.Cegielski-Poznań S.A" (1996-98), which was crowned by starting up the series production of Poland's largest 650kW 8A20G gas engine at the Works of H.Cegielski-Poznań S.A., as the chief executor of this project. In the years 1998-2005, he commercially operated a biogas cogeneration set equipped with this engine at the WARTA S.A. Waste Treatment Plant in Czestochowa.

The author is convinced that the results of the completed research project, which are included in the monograph, will make it possible to better and more reliably assess the real advantages possible to be achieved through the use of gas cogeneration sets, and will certainly help to reduce the risk of making a major technical and economic mistake by the present and future users of such sets, and may also facilitate the operation of cogeneration sets by their future users. Edited in full colour, the monograph is very richly illustrated, which substantially enhances its value. Enclosure to [2] presents some companies active in the Polish market, which offer gas cogeneration sets;

these are: Centrum Elektroniki Stosowanej CES Sp. z o.o. of Krakow; ENER·G Polska Warszawa, KWE - Technika Energetyczna Sp. z o.o., the Authorized Representative of GE Jenbacher Gas Engines Division in Poland – Bielsko-Biała; and P.P.U.H. Horus-Energia Sp. z o.o. – Sulejówek; along with a brief description of piston engine gas cogeneration set projects completed by them in recent years.

This monograph is intended for those interested in the design, construction and operation of gas cogeneration sets generating, in combination, electrical energy, heat and refrigeration, and specifically for engineering and technical personnel, both the present and the future users of gas cogeneration sets with piston engines. It is a valuable complement to, sparse in the Polish market, scientific publications on gas cogeneration, and, being the source of reliable and practically unavailable information on the actual conditions of operation of gas cogeneration sets, it will undoubtedly facilitate the estimation of the reliable technical & operational parameters and economic effectiveness of a gas cogeneration set already at the stage of its selection, and the viability of the planned investment project. The monograph may also prove helpful for Power Engineering course students.

A continuation of the subject matter addressed in [2] is publication [3] „A summary of twelve months' operation of the new biogas cogeneration set in WARTA S.A. Waste Treatment Plant in Czestochowa". In a convention similar to that in [2, 1], one-year operation of the GE Jenbacher JMS 316 GS-B.LC (828 kW_e/870 kW_t) engine biogas cogeneration set started up in December, 2008, in the recently modernized WARTA S.A. Waste Treatment Plant of Czestochowa is analyzed in detail. The supplier of the engine was the company KWE - Technika Energetyczna Sp. z o.o. of Bielsko-Biała, the Authorized Representative of GE Jenbacher Gas Engines Division in Poland.

3. Conclusion

- Biogas acquired from the waste treatment plant as a sewage sludge digestion by-product, landfill gas, and coal-mine gas are all valuable fuels that can be effectively utilized on site for supplying piston engine gas CHP sets.
- The energy utilization of gaseous fuels (such as biogas, landfill gas, or coal-mine gas) in CHP sets definitely reduces the emissions of pollutants to the atmosphere by minimizing practically to zero the emission of the greenhouse gas, methane, at the source of its generation, and brings about measurable economic benefits associated with the purchase of electrical energy and heat for the internal purpose of companies, as well as with the sale of their property rights obtained from the Certificates of Origin of energy.
- When planning a piston engine gas cogeneration set, a gaseous fuel recovery technology should be implemented, which will guarantee the appropriate quality of the fuel (silicon compounds, H2H), thus reducing the current costs of CHP operation in the future by extending the operation period and reducing oil consumption and wear of gas engine parts.
- The gas cogeneration sets described in the monograph, which are manufactured by companies, such as Deutz, GE Jenbacher, and MAN, are characterized by a high level of technological advancement and reliability, as confirmed by their high degree of utilization and operation under loads comparable to the rated values, with their operation generally not posing any technical difficulties.
- The technical servicing of gas CHP sets (including ongoing monitoring of gaseous fuel and oil quality), if conducted correctly and following the manufacturer's recommendations, ensures that they will be maintained in constant technical readiness guaranteeing the high degree of their utilization under loads close to the rated values, and will also provide grounds for any warranty claims to be recognized by the manufacturer.
- From the performed analysis it can be concluded that the cooperation of the gas CHP set users with both the gas CHP set manufacturers and with the companies carrying out investment tasks can generally be assessed as positive and constructive, this being particularly true for quick responding and repairing any occurring failures in an ongoing basis.

- If follows from the talks with numerous domestic operators of Western gas cogeneration sets that the current servicing costs (spare parts and labour) of these sets make up a very significant components of their operational costs, and the total servicing cost from the start-up to the first major repair can be estimated at about 50% of the purchase price of a new CHP set. This situation is due to the high cost of original spare parts offered by the manufacturers and the manufacturer's service labour cost, as well as the restriction of the manufacturers as to the scope of service work allowed to be done by the user's technical services (without making the warranty invalid). So, when planning the purchase, commissioning and operation of a gas CHP set, one must be aware of the fact that this will involve significant costs which cannot be omitted in drawing up the business plan for gas cogeneration sets. When negotiating the terms and conditions of a contract, an endeavour should be made to include such provisions in the contract, which will allow the user's technical services, upon being appropriately trained by the manufacturer, to carry out operation & maintenance work in the largest possible scope.
- The analysis of the operation of selected gas CHP sets showed that the gauging of the heat recovery system in the water-water and combustion gas-water heat exchanger was complete in each case, which prevented the detailed calculation of economic effects resulting from the generation of heat.
- The correct incorporation of gas CHP sets into the electric power and heating systems of industrial plants operating those gas CHP sets will enable the production of electrical energy and heat (or refrigeration) to be maximized. These energy carriers, used for the plant's internal purposes, at the same time significantly reduce their purchases from external suppliers, thus improving their average external purchase price.
- The presented in the monograph technical solutions of the installation with gas CHP sets and piston engines, which have been proven in industrial practice, and whose technical advancement and reliability have been confirmed by substantial economic effects obtained from their operation, are worth recommending as model ones for implementing in the future in other domestic facilities with characteristics (fuel, internal needs) similar to those described in the monograph.
- As a result of the correctly conducted operation of gas CHP sets, the current operational costs of plants operating those gas CHP sets were significantly reduced in many cases, chiefly owing to: reducing the purchases of electrical energy and heat from external suppliers, utilizing the whole heat produced by cogeneration for the plant's internal purposes, ceasing purchasing fuel oil for the plant's boiler-room, obtaining the entry to the list of "green energy" producers and obtaining regularly URE Certificates of Origin for RES-generated electrical energy, which can be advantageously sold by their holders at TGE S.A.
- The results of the analysis of the actual technical and operational parameters of piston engine CHP generation sets, which are presented in the monograph, may provide a significant assistance to the future operators of such sets already at the SIWZ (Specification of essential public procurement conditions), as required under the Act of 29 Jan., 2004 – Public procurement law, with subsequent amendments.

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