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The analysis of a Velox-type CHP plant for various gaseous fuels

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Abstract. For many years, the Institute of Power Engineering and Turbomachinery of the Silesian University of Technology has been using a small-capacity (about 500 kW_e) steam-gas power plant. Based on many years of experience in operation of this power plant utilizing the Velox-type gas-steam system, an idea arose to modify this type of thermal power cycle to create a combined heat and power (CHP) plant of small capacity, dedicated for distributed heat and power production of the range up to 500 kW or production process steam with high temperature. Previous thermodynamic and economic analysis of that type of CHP plant were conducted for natural gas as a fuel. The new idea is use the alternative gas fuels or waste heat for Velox-type CHP plant. An adaptation of the Velox-type CHP plant for various fuels can be done in simple way by moving the combustion chamber out from the set of heat exchangers, in similar way as it is done for HRSG. This paper presents a thermodynamic analysis of the Velox-type steam-gas cycle fired with various alternative gas fuels such as coke gas, blast furnace gas, biogas or gas from gasification. The systems are modelled in the EBSILON® Professional 13 program.

1 Introduction

Historically, the first idea for combining gas and steam turbine cycles was to install a steam generator in place of the gas turbine combustion chamber. This concept was put forward by the Brown Boveri company, which patented the Velox-type gas-steam system in 1932. In 1939, a gas turbine was used for the first time in the world to produce electricity. It was also the first gas-steam system used for electricity generation [1, 2].

Considering the amount of steam generated, the Velox-type steam generator is characterized by a compact structure and relatively small heat transfer surface area, especially in the evaporator. This is due to the fact, that the heat exchange process in the combustion chamber takes place in overpressure, which intensifies the heat transfer between exhaust gases and water and steam in the tubes of the evaporator or steam superheaters. The high velocity of the exhaust gas enabled effective use of the combustion chamber surface area [2]. The implementation of this type of steam generator in power engineering made it possible to create highly efficient plants generating electricity and heat, i.e., the first combined heat and power plant (CHP plant) [1, 3].

For many years, the Institute of Power Engineering and Turbomachinery of the Silesian University of Technology has been using a small-capacity (about 500 kW_e) steam-gas power plant of a Velox-type cycle for purposes related to both teaching and experimental testing of steam condensing flows [4]. The experience gained so far from the operation of this power plant based on a Velox-type gas-steam system confirms very good flexibility of the system operation, the short time

needed to prepare live steam with required parameters, the parameters stability and the fast rate of load change.

Based on this an idea arose to modify this type of thermal power cycle to create a combined heat and power (CHP) plant of small capacity, dedicated for distributed heat and power production of the range up to 500 kW or production process steam with high temperature. Previous thermodynamic and economic analysis [5, 6] of that type of CHP plant fired with natural gas, and compared with classical gas-steam cycle [7, 8] led to conclusions:

- Velox-type plant can operate for much less load than classical CHP plant,
- Velox-type steam-gas unit creates an opportunity to use higher temperatures of live steam,
- Velox-type plant can operate for much less load than classical CHP plant,
- Velox-type plant can be much cheaper than classical CHP plant.

The new idea is use the alternative gas fuels or waste heat for Velox-type CHP plant. An adaptation of Velox-type CHP plant for various fuels can be done in simple way by moving on combustion chamber out from the set of heat exchangers.

This paper presents a thermodynamic analysis obtained by modelling the Velox-type steam-gas cycle fired with various alternative gas fuels in the EBSILON® Professional 13 program.

The considerations presented herein concern small-capacity power plant with the power output of the order of a few megawatts of electric power, intended for distributed generation of electricity and heat based on the various gas fuel.

2 Thermal power cycle and parameters

The Velox-type CHP plant (Fig. 1) is characterized by a much higher ratio of electricity obtained from the steam turbine and the gas turbine, respectively, compared to classical gas-steam cycles which are now in use. From the same amount of fuel more steam with higher enthalpy is produced [6]. The Velox-type CHP plant systems was modelled in the EBSILON® Professional 13 program according to technological structure depicted in the Fig. 1.

In Table 1 the basic parameters are presented for nominal load of the Velox-type CHP plant under consideration. It sets out all important parameters for cycle presented above, as well as efficiency of main and auxiliary machines.

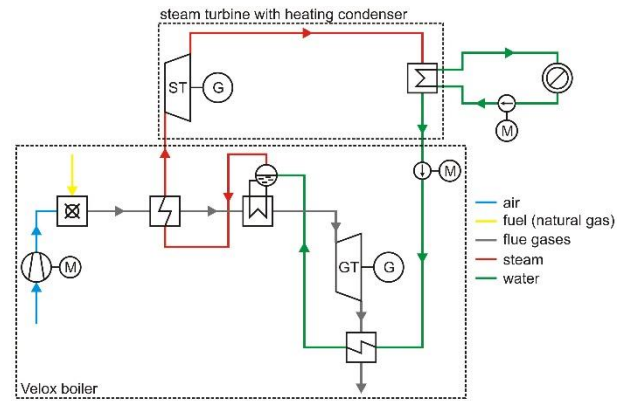


Fig. 1. Velox-type CHP plant scheme.

Table 1. Basic operating parameters for the Velox-type CHP plant under consideration (nominal load).

Parameter	Value	Unit
Air pressure upstream the compressor	0.1	MPa(a)
Air temperature upstream the compressor	20	°C
Air mass flow	0.1	kg/s
Air pressure downstream the compressor	0.3	MPa(a)
Fuel pressure upstream the combustion chamber	0.3	MPa(a)
Fuel temperature upstream the combustion chamber	20	°C
Exhaust gas temperature downstream the combustion chamber	700	°C
Exhaust gas pressure downstream the gas turbine	0.1	MPa(a)
Live steam temperature	680	°C
Live steam pressure	2	MPa(a)
Steam temperature downstream of the steam turbine	265	°C
Steam pressure downstream the steam turbine	0.1	MPa(a)
Inlet temperature of the heating water circuit	30	°C
Outlet temperature of the heating water circuit	94.6	°C
Gas turbine internal efficiency	90	%
Steam turbine internal efficiency	90	%
Efficiency of generators	98.6	%
Compressor efficiency	85	%
Efficiency of pumps	80	%
Electric efficiency of motors driving the pumps and compressor	95	%
Mechanical efficiency of motors (for pumps and compressor)	99.8	%

3 Considered gas fuels

Four types of alternative gas fuels, already successfully used in the production of electricity and heat, were selected for the analysis of the Velox-type CHP plant work. These are biogas, blast furnace gas, coke gas and syngas from coal gasification. In addition, two different syngases obtained from the most popular gasification processes were selected to analyse the Velox-type CHP

plant work with syngas. Thus, a total of five selected gaseous fuels were analysed.

Brief characteristics of each of these fuels together with volume fractions and calculated calorific value are presented below. The calorific values of each of the gaseous fuels discussed below were calculated in the EBSILON® Professional 13 program automatically after entering presented volume fractions of individual components of the gas mixture, and these values were adopted for further analysis.

3.1 Biogas

Biogas is the mixture of gases produced by the breakdown of organic matter in the absence of oxygen. It can be produced from raw materials such as agricultural waste, manure, municipal waste, plant material, sewage, green waste or food waste. Biogas is primarily methane and carbon dioxide and may have small amounts of hydrogen sulfide, moisture and siloxanes [9].

Because of low calorific value and flame speed biogas is found to be worse fuel than the conventional fuels, therefore it is often enriched by hydrogen or methane.

For our analysis we have decided to use biogas from work [10]. The composition of this biogas is presented in Table 2.

Table 2. Composition of biogas used for analysis [10].

Component	Value	Unit
CH ₄	49.777	Volume %
CO ₂	43.535	Volume %
CO	1.197	Volume %
H ₂	0.489	Volume %
N ₂	4.759	Volume %
O ₂	0.243	Volume %
Calorific value	13977.464	kJ/kg

3.2 Blast furnace gas

Blast furnace gas is a by-product of blast furnaces that is generated when the iron ore is reduced with coke to metallic iron. It has a very low heating value because it consists of about 60 percent nitrogen and 18-20% carbon dioxide, which are not flammable. The rest is mostly carbon monoxide, which has a fairly low heating value already and some hydrogen [11].

It is commonly used as a fuel within the steel works, but it can be used in boilers and power plants equipped to burn it. It may be combined with natural gas or coke oven gas before combustion or a flame support with richer gas or oil is provided to sustain combustion. Because of the high concentration of carbon monoxide blast furnace gas is hazardous.

Composition of blast furnace gas used in our analysis is presented in Table 3 and the source of the volume fractions values is paper [12].

Table 3. Composition of blast furnace gas used for analysis [12].

Component	Value	Unit
CO ₂	20.09	Volume %
CO	23.74	Volume %
H ₂	2.05	Volume %
N ₂	53.41	Volume %
O ₂	0.71	Volume %
Calorific value	2348.173	kJ/kg

3.3 Coke gas

Coal gas is a flammable gaseous fuel made from coal. It is a by-product of the coking process and it is produced when coal is heated strongly in the absence of air. Coal gas contains a variety of calorific gases including hydrogen, carbon monoxide, methane, ethylene and volatile hydrocarbons together with small quantities of non-calorific gases such as CO₂ and N₂ [13].

Because of high amount of CH₄ and H₂ coke gas has a higher calorific value than other alternative gas fuels. Due to this fact, coal gas can be supplied to the user via a piped distribution system in the same way as natural gas.

The coke gas used in our analysis is produced in steel plant placed in Krakow, Poland [14]. Composition of this gas is presented in Table 4.

Table 4. Composition of coke gas used for analysis [14].

Component	Value	Unit
CH ₄	23.7	Volume %
CO ₂	2.6	Volume %
CO	6.6	Volume %
H ₂	57.3	Volume %
N ₂	7.2	Volume %
O ₂	0.2	Volume %
C _n H _m	2.4	Volume %
Calorific value	35498.049	kJ/kg

3.4 Syngas

Syngas is a fuel gas mixture consisting primarily of hydrogen, carbon monoxide, and very often some carbon dioxide. Syngas is usually a product of coal gasification and the main application is electricity generation. Syngas is combustible and can be used as a fuel of internal combustion engines. Syngas has less than half the energy density of natural gas [15].

Syngas can be produced from many sources, including natural gas, coal, biomass, or virtually any hydrocarbon feedstock, by reaction with steam (steam reforming), carbon dioxide (dry reforming) or oxygen (partial oxidation).

Due to the fact, that in Poland we still have large coal reserves, which can be used in electricity and heat production, we have decided to use in our analysis only syngas from two most popular coal gasification processes. It means from Koppers–Totzek gasification system and Lurgi gasification system.

3.4.1 Koppers-Totzek gasification

The Koppers-Totzek gas generator is based on a turbulent flux. Coal is supplied to direct-flow reactors together with gasifying agents – steam and oxygen. The reactor is at elevated pressure and temperature. In contrast to processes with a compact bed, the use of turbulent flux permits the gasification of different types of coal and produces gas at high temperature; the gas is free of tars and phenol [15].

Composition of syngas obtained from Koppers-Totzek gasification process used in the analysis is presented in Table 5.

Table 5. Composition of syngas Koppers-Totzek used for analysis [15].

Component	Value	Unit
CO ₂	65.2	Volume %
CO	0.8	Volume %
H ₂	25.5	Volume %
N ₂	8.2	Volume %
H ₂ S	0.3	Volume %
Calorific value	11507.881	kJ/kg

3.4.2 Lurgi gasification

One of the commonest and oldest-established technologies is gasification in a steady bed by the Lurgi method. Gasification in a dense fuel bed at atmospheric pressure extracts practically all of the valuable components. Gasification of a dense bed of coal pieces at elevated pressure is also employed [15].

Composition of syngas obtained from Lurgi gasification process used in the analysis is presented in Table 6.

Table 6. Composition of syngas Lurgi used for analysis [15].

Component	Value	Unit
CH ₄	7.6	Volume %
CO ₂	2.6	Volume %
CO	60.6	Volume %
H ₂	27.8	Volume %
N ₂	1.0	Volume %
C _n H _m	0.4	Volume %
Calorific value	15245.344	kJ/kg

4 Thermodynamic analysis of a Velox-type CHP plant for considered gas fuels

Figures 2, 3 and 4 and Table 7 shows a comparison of the calculated, selected thermodynamic parameters for the nominal load of the analysed Velox-type CHP plant working with the gaseous fuels presented above.

Fig. 2 shows a comparison of cycle efficiency with a breakdown into the efficiency of electricity and heat generation. The total cycle efficiency, depending on the fuel used, remains basically unchanged and fluctuates slightly within 77%. Larger differences can be seen in the efficiency of generating electricity or heat alone. It can be seen here that the cycle fired with blast furnace gas demonstrate the highest efficiency of electricity generation. This efficiency is 23.8%, compared to approximately 20.5% for other cases. However, the heat generation efficiency is reduced for this case. For a cycle fired with blast furnace gas it is 53.8%, compared to approximately 56% for other cases.

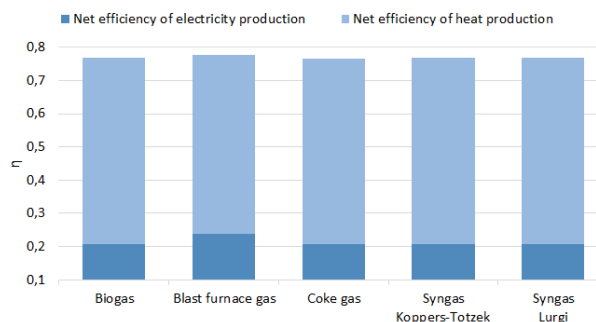


Fig. 2. Efficiency for nominal load of the thermal cycle fired with gas fuels under consideration.

For the cycle fired with blast furnace gas compared to other cases, higher production of both electricity and heat was noticed (see also Fig. 6). At the same operating parameters, such as pressure and temperature of steam and exhaust gases, for each case, these differences are obviously associated with both exhaust gas and steam mass flow rates. As can be seen in Fig. 3 primarily the exhaust gas mass flow rate for a cycle fired with blast furnace gas is much larger compared to other cases, hence more exhaust gas energy can be converted into useful work here.

However, the production of larger amounts of exhaust gas is associated with largest demand for fuel, the more that blast furnace gas has the lowest calorific value of all fuels analysed here. Additionally, in Fig. 3 we can see that for the nominal load of the analysed Velox-type CHP plant, the least fuel should be supplied to the cycle fired with coke gas (0.0018 kg/s) and this is not much more than for previously conducted analyses for natural gas [6]. The next in order are cases fired with fuels: syngas Lurgi (0.0042 kg/s), biogas (0.0047 kg/s), syngas Koppers-Totzek (0.0057 kg/s) and at the very end the already mentioned blast furnace gas (0.0376 kg/s). Considering the calorific values of individual considered gaseous fuels, this order should have been expected.

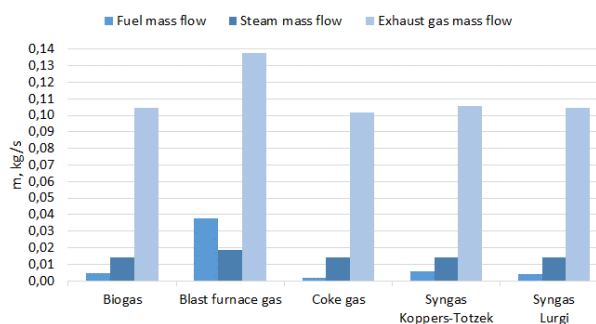


Fig. 3. Mass flow rates for fuel, steam and exhaust gas for nominal load of the thermal cycle fired with gas fuels under consideration.

It should also be noted that the larger mass flow rates of exhaust gases or steam, the heat exchange surfaces also increase (Fig. 4 and Table 7). In Fig. 4 and Table 7 we can also see that the largest heat exchange area should be provided for the heat exchanger in the heating water circuit for the cycle fired with blast furnace gas. This cycle, compared to other cases, would also need the

largest heat exchange areas in the economizer, evaporator and superheater. Other cases have heat exchange surfaces very similar, therefore a change of

fuel for the Velox-type CHP plant under consideration would not require major structural changes, except for the use of blast furnace gas as a fuel.

Table 7. Surface area of the heat exchangers (kA parameter) of the thermal cycle fired with various gas fuels (nominal load).

Parameter	Biogas	Blast furnace gas	Coke gas	Syngas Koppers-Totzek	Syngas Lurgi	Unit
Economizer	0.241	0.322	0.232	0.239	0.236	kW/K
Evaporator	0.131	0.168	0.127	0.130	0.128	kW/K
Superheater	0.129	0.168	0.126	0.128	0.127	kW/K
Heat exchanger in the heating water circuit	1.503	1.951	1.462	1.493	1.478	kW/K
Sum	2.003	2.610	1.947	1.990	1.969	kW/K

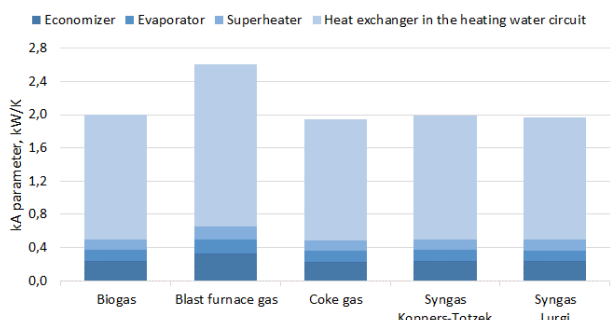


Fig. 4. Surface area of the heat exchangers (kA parameter) for nominal load of the thermal cycle fired with gas fuels under consideration.

Figures 5 – 9 presents the operational characteristics of Velox-type CHP plant working with the gaseous fuels under consideration for various loads. From the analysis of these figures, it can be concluded that for each fuel the operating range of the considered cases is very similar. The flexibility of the Velox-type CHP plant fired with various gaseous fuels is again confirmed, as it was for natural gas in earlier analysis presented in [6].

In addition, in Fig. 6 it can be also seen a slightly larger operating range for the cycle fired with blast furnace gas, compared to other cases, as well as greater production of both electric power and thermal power, and slightly greater efficiency, which has already been shown for nominal load and is associated with energy flow for this case.

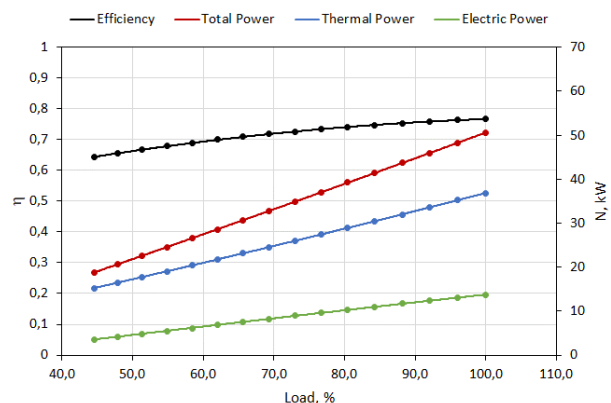


Fig. 5. Operational characteristics of the Velox-type CHP plant fired with biogas for different loads.

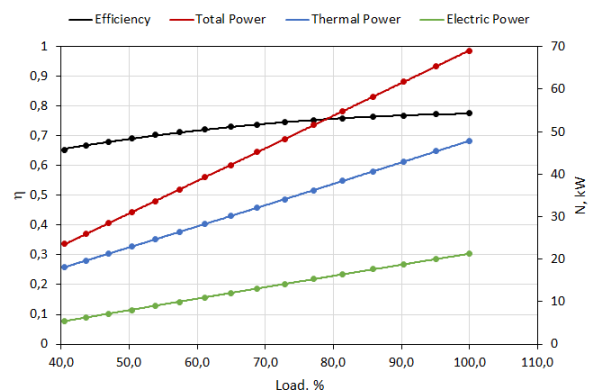


Fig. 6. Operational characteristics of the Velox-type CHP plant fired with blast furnace gas for different loads.

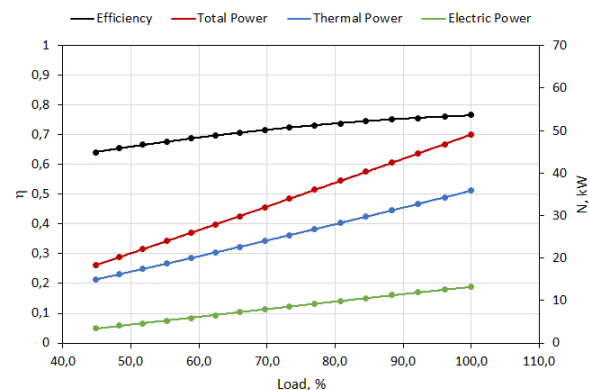


Fig. 7. Operational characteristics of the Velox-type CHP plant fired with coke gas for different loads.

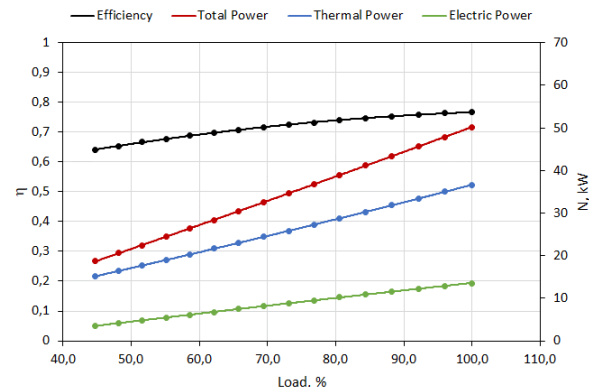


Fig. 8. Operational characteristics of the Velox-type CHP plant fired with syngas Koppers-Totzek for different loads.

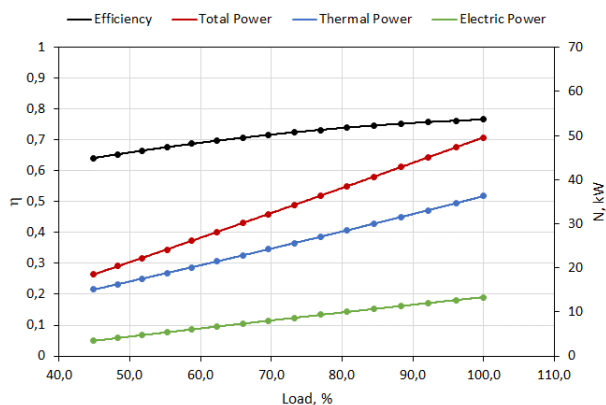


Fig. 9. Operational characteristics of the Velox-type CHP plant fired with syngas Lurgi for different loads.

5 Conclusions

Obtained results from the analysis of the work of Velox-type CHP plant fired with alternative gaseous fuels led to the following conclusions:

- the cycle under consideration can work successfully with any of the proposed unconventional gaseous fuels,
- for the same operating parameters assumed for each case, the largest demand for fuel is shown for the cycle fired with blast furnace gas,
- also the cycle fired with blast furnace gas would be the largest CHP plant due to the largest heat exchange areas required for each of the heat exchanger used,
- the cycles fired with biogas, coke gas and both types of syngas could work with any of these fuels without major structural changes.

Thus, Velox-type CHP plant creates great opportunities for distributed generation of electricity and heat with the power output of the order of a few megawatts. This cycle can be adapted at a low cost to work with each of the alternative gas fuels under consideration.

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