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The performance of a steam-gas power unit of a velox-type cycle

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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 Velox-type small-capacity gas-steam power unit for teaching and research purposes. The Velox-type gas-steam cycle is characterized by a much higher ratio of power obtained from the steam turbine and the gas turbine, respectively, compared to classical gas-steam cycles which are now in use worldwide. This paper presents a thermodynamic analysis of the Velox-type gas-steam cycle as a small capacity combined heat and power plant (CHP). The systems are modelled in the EBSILON® Professional. The advantages and drawbacks of the Velox-type cycle compared to the classical one are presented.

Keywords: Velox; gas-steam cycle; CHP; HRSG

1. Introduction

Historically, the first idea for combining gas and steam turbine cycles was to install a steam generator in the gas turbine cycle to replace the 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. The installation in Neuchâtel (Switzerland) was built by the Brown Boveri company established in Baden, Switzerland in 1891 by Charles E.L. Brown and Walter Boveri. 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]. Live steam parameters in those units ranged from 15 to 135 bar(a), the temperature reached 500°C, and the output was from 15 to 200 t/h, which in the 1930s was quite an accomplishment (Fig. 1 left).

The experience gained to date from operating the power plant based on a Velox-type gas-steam system installed in the Institute of Power Engineering and Turbomachinery of the Silesian University of Technology (Fig. 1 right) confirms the very good operational flexibility of the system, i.e., the short time needed to prepare live steam with the required parameters, the parameters' stability and the fast rate of change in loads. Based on this, an idea arises to modify this type of thermal power cycle to create a small capacity combined heat and power (CHP) plant, dedicated for distributed heat power production in the range of tens of kilowatts.

The proposed Velox-type CHP plant will be compared with the most popular combined gas-steam power plant using a gas turbine, the heat recovery steam generator (HRSG) to generate steam and the steam turbine cycle [4].

2. Considered CHP plant—thermal power cycles and parameters

The Velox-type CHP plant (Fig. 2 top) 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 (Fig. 2 bottom). From the same amount of fuel more steam with higher enthalpy is produced.

The main difference between the cycles is the position of the gas turbine expander. In the classical gas-steam cycle the expander is located straight downstream of the combustion chamber, as in the typical gas turbine engine [4, 5]. In

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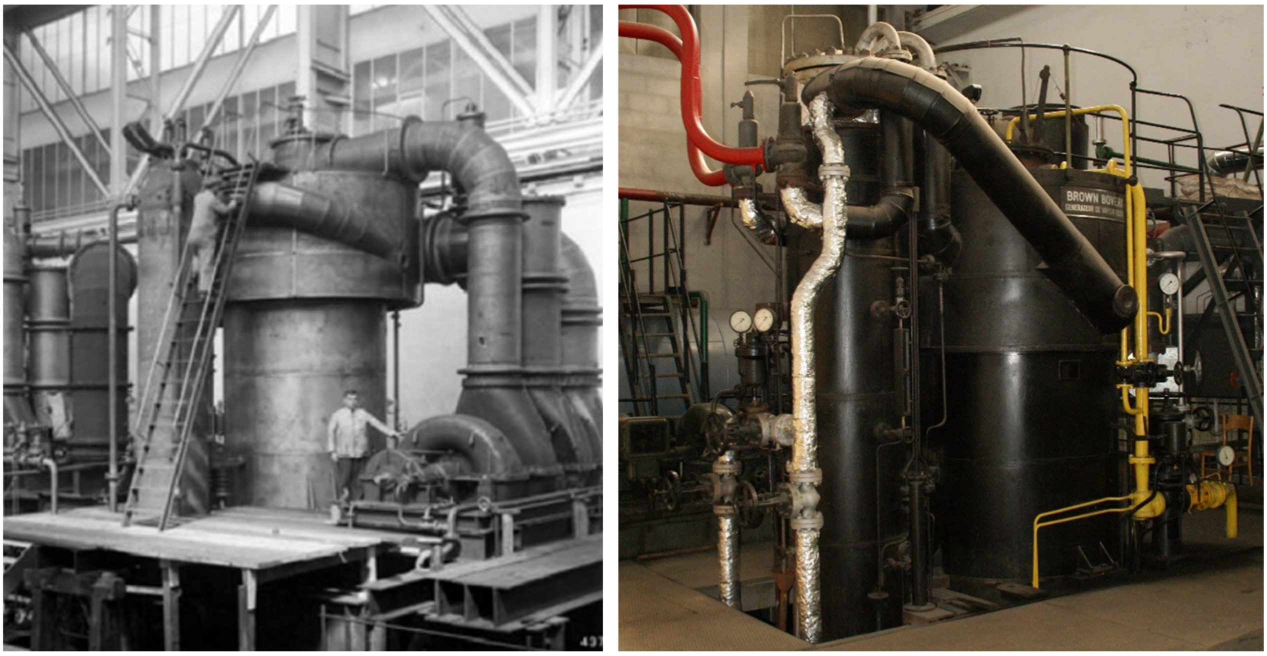

Figure 1: Velox-type system; in Baden power plant (1936) [2]—left, and at Silesian University of Technology [3]—right

the Velox-type the expander is situated between the evaporator and the economizer. This position means the live steam has a higher temperature ahead of the steam turbine, but it also results in lower power generated in the gas expander. The shaft coupling for the expander and compressor cannot be used for the Velox-type cycle, because for the lower load the expander may generate less power than is needed to drive the compressor. Also, in the Velox-type cycle there is only a 10% larger total heat exchange area in the water/steam cycle for significantly higher heat flux in the heating water circuit. This contributes to the lower investment cost of the Velox-type cycle compared to the traditional gas-steam cycle with HRSG [4, 5], taking into account the same amount of hot water production in both thermal cycles. In the case of the Velox-type cycle (Fig. 2 top), the separate configuration of the expander and compressor means the lobe or cam type of these machines can be used. It is much less expensive than a gas turbine engine and much more available on the market, due to there being plenty of producers.

In Table 1 the basic parameters are presented for nominal load of the Velox-type and classical CHP plants. It sets out all important parameters for both cycles, as well as the power and efficiency. Net efficiency of the electricity production is not high in either case, which is to be expected for these types of small capacity cycles. Nevertheless, the efficiency of cogeneration lies within the range of many other CHP plants with different technological structures [6]. The efficiency of heat and power production for the Velox-type plant is higher than for the classical one. The total amount of electricity production in Velox-type plant is less than in the classical gas-steam CHP plant, whereas the heat flux in the heating water circuit is higher.

Table 2 shows the parameter kA for all used heat exchangers in both CHP plants. It can be used to assess the heat exchangers' surface area. The Velox-type CHP plant have only a 10% larger heat exchange area than the CHP plant with gas turbine and HRSG.
Table 1 shows that for the gas-steam cycle with HRSG the exhaust gas temperature downstream of the economizer (exhaust to the chimney) is higher than for the Velox-type cycle. However, in both cases consideration could be given to implementingwaste heat utilization, e.g., in the ORC cycle. The minimum temperatures of exhaust gas exiting to the chimney for the Velox-type and the gas-steam with HRSG are 108 and 150°C, respectively.

3. Operational characteristics

In both considered CHP plants a steam turbine operates with sliding-pressure, i.e., the live steam mass flow, temperature and pressure follow the change in the amount of fuel delivered to the burners of the combustion chamber, and vice versa. It requires the use of an electric motor with inverter drive for the feed water pump.

Fig. 3 presents the characteristics of both CHP plants under consideration. One can observe a much wider range of load for the Velox-type plant. For the power unit with gas turbine engine and HRSG the lowest load is limited by the minimum temperature of the turbine exhaust gas.

Fig. 4 shows the influence of the steam turbine back pressure on the efficiency and total power for both CHP units. One can conclude that change in back pressure does not affect the heat flux significantly, but higher back pressure lowers efficiency due to the lower power generated in the steam turbine.

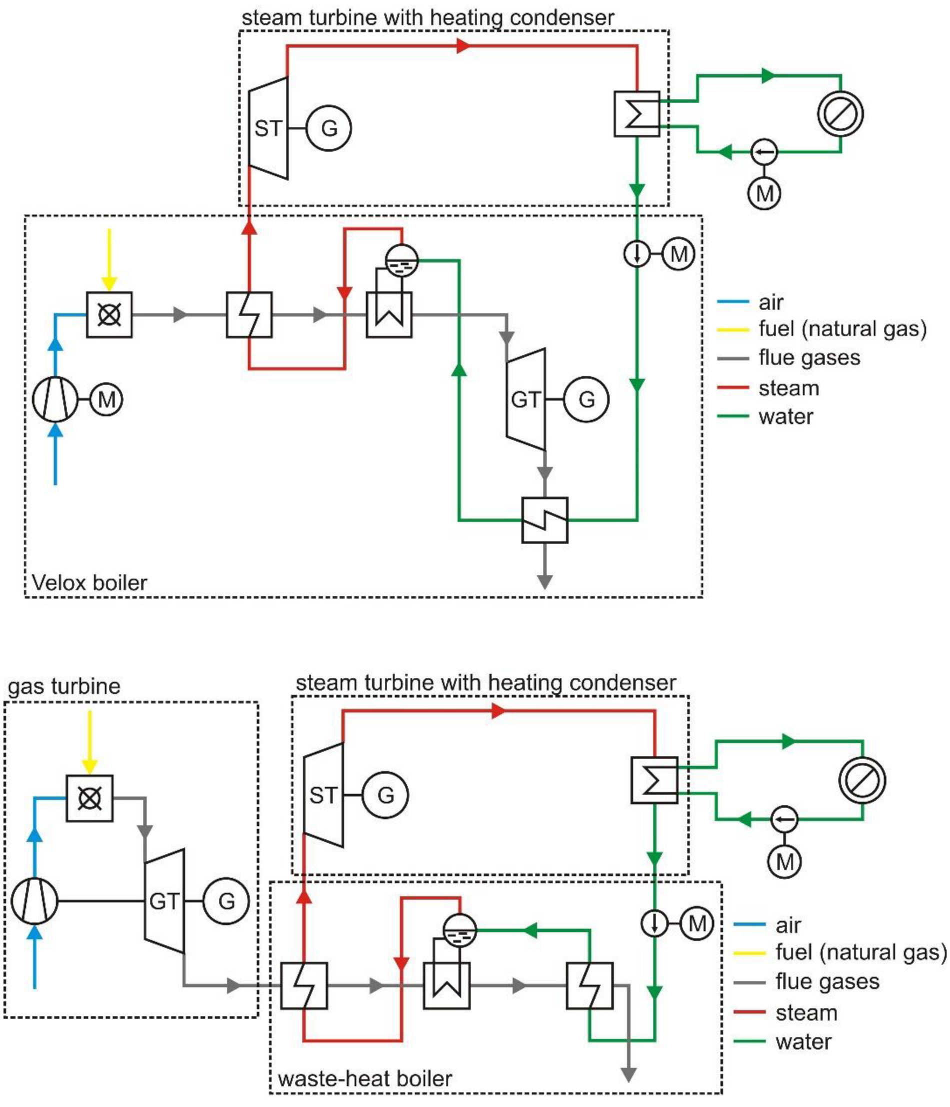

Figure 2: Velox-type CHP plant (top) and a gas-steam CHP plant using a waste-heat boiler (bottom)

Table 1: Basic operating parameters calculated for the thermal cycles under consideration for nominal load

Parameter	Velox-type CHP plant	Classical gas-steam CHP plant	Unit
Fuel mass flow rate	0.0013	0.0013	kg/s
Exhaust gas mass flow rate	0.101	0.101	kg/s
Exhaust gas temperature upstream of the expander	333	700	°C
Exhaust gas temperature downstream of the expander	192	489	°C
Live steam temperature	680	493	°C
Live steam pressure	2000	2000	kPa(a)
Steam mass flow	0.014	0.012	kg/s
Steam temperature downstream of the steam turbine	265	133	°C
Power on the compressor shaft	12.989	-	kW
Power on the feed water pump shaft	0.034	0.029	kW
Power on the heating water circuit pump shaft	0.008	0.006	kW
Power on the gas turbine shaft	15.141	11.581	kW
Power on the steam turbine shaft	11.897	7.744	kW
Inlet temperature of the heating water circuit	30	30	°C
Outlet temperature of the heating water circuit	94.6	94.6	°C
Heat flux from the heating water circuit	35.547	27.446	kW
Exhaust gas temperature downstream of the superheater	576	427	°C
Exhaust gas temperature downstream of the evaporator	333	223	°C
Exhaust gas temperature downstream of the economizer	146	171	°C
Water temperature upstream of the economizer	99.9	99.9	°C
Water temperature downstream of the economizer	184	208	°C
Steam temperature downstream of the evaporator	213	213	°C
Gas turbine internal efficiency	90	90	%
Steam turbine internal efficiency	90	90	%
Efficiency of generators	98.6	98.6	%
Compressor efficiency	85	85	%
Efficiency of pumps	80	80	%
Electric efficiency of motors driving the pumps	95	95	%
Mechanical efficiency of motors (for pumps and compressor)	99.8	99.8	%
Net efficiency of electricity production	20.4	30.1	%
Net efficiency of heat and electricity production	76.7	73.5	%

Table 2: Surface area of the heat exchangers (kA parameter) for the thermal cycles under consideration for nominal load

Parameter	Velox-type CHP plant	Classical gas-steam CHP plant	Unit
Economizer	0.230	0.152	kW/K
Evaporator	0.126	0.339	kW/K
Superheater	0.125	0.087	kW/K
Heat exchanger in the heating water circuit	1.449	1.119	kW/K
Sum	1.930	1.697	kW/K

4. Design solutions

As shown above, the Velox-type and classical gas-steam CHP plant differ significantly in terms of the size of the heat transfer surface area. In the Velox-type unit, the heat exchangers of the evaporator and superheater are located inside the combustion chamber, like in most steam boilers (Fig. 5, top). In contrast, in the gas-steam cycle with HRSG all of the heat exchangers are arranged one by one along the exhaust gas flow path, either horizontally or, less frequently, vertically (Fig. 5, bottom).
The Velox burner and heat recovery steam generator were assumed to be drum boilers with natural circulation of water in the evaporator.

Due to the different arrangement of heat exchangers in the systems under consideration must contribute to the differences in the total surface of heat exchange. For the reference variant of the Velox-type cycle, the entire heat transfer surface area is about 10% higher than the HRSG in the classical gas-steam system.

5. Conclusions

This paper discusses a thermodynamic analysis of two small capacity CHP plants. The characteristics for different loads were presented and design concepts of the steam generators shown. The systems were modelled in the EBSILON® Professional. The calculations performed lead to the following conclusions:

1. The main power of the Velox-type steam-gas unit is generated in the steam cycle, which is not the case in the classical gas-steam cycle. This is caused by the fact that the Velox-type steam-gas unit creates an opportunity to use higher temperature live steam.
2. The surface area of the heat exchangers in the classical gas-steam unit is more than 10% smaller than in the Velox-type steam-gas unit, which is not a big difference as the difference is due to the size of the heat exchanger in the heating water circuit.
3. The Velox-type steam-gas unit can use a much less expensive compressor and expander of the gas cycle, and design of the combustion chamber, including burners, lies within the manufacturing capabilities of many small companies.
4. Operating experience highlights the following positive features of the Velox-type gas-steam system: good flexibility and fast rate of changes in loads, which is of

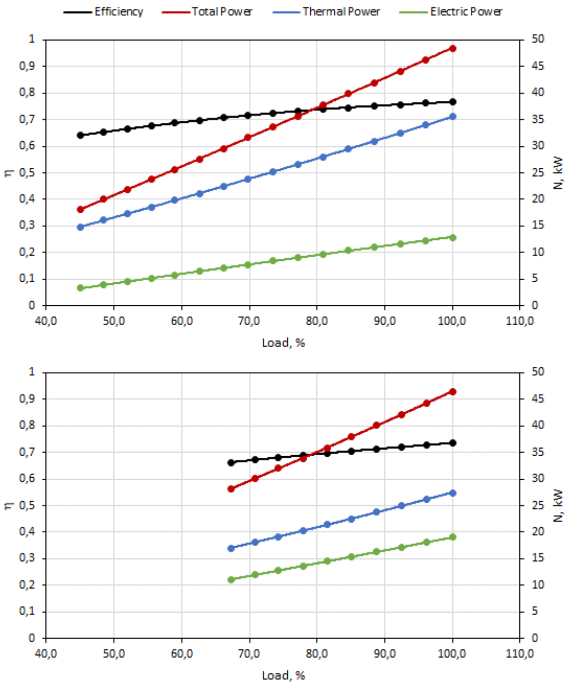

Figure 3: Operational characteristics of the Velox-type CHP plant (top) and classical gas-steam CHP plant (bottom) for different loads

fundamental importance for small power capacity cycles operating in distributed systems or generating own-needs electricity. The Velox-type plant can operate at a much lower load than the classical CHP plant.

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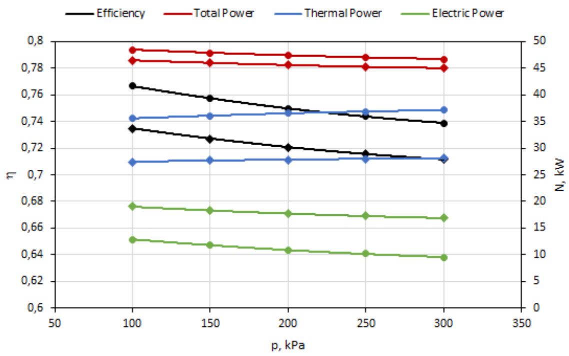

Figure 4: Influence of the steam turbine back pressure on the operation of the CHP plant (dots—Velox-type, diamonds—classical gas-steam CHP plant)

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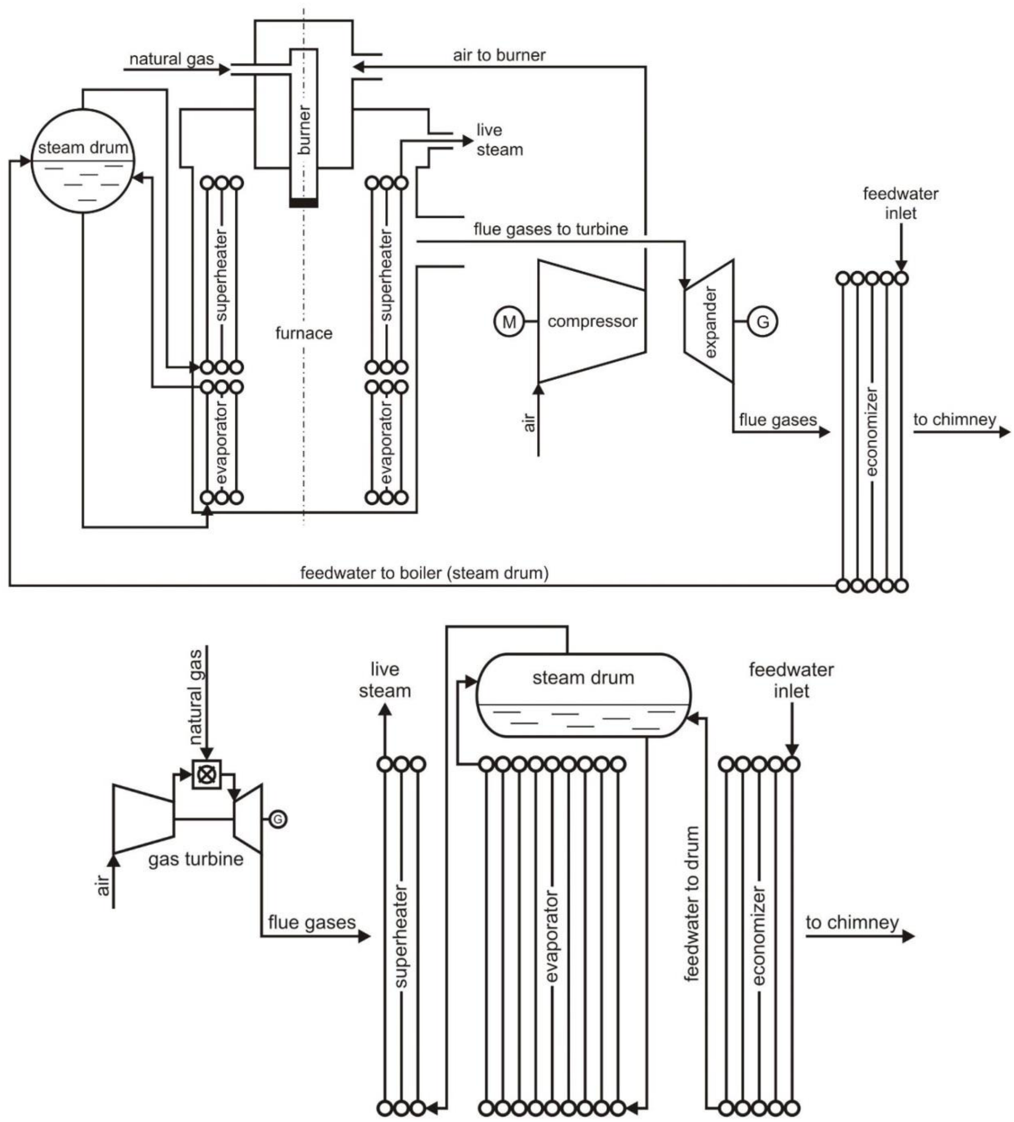

Figure 5: Arrangement of heat exchangers in the boiler; Velox-type steam-gas cycle—top, classical gas-steam cycle—bottom