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Mathematical model of Combined Heat and Power Plant using GateCycle$^{\text{TM}}$ software

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Abstract

The This paper contains a description and analysis of a mathematical model of the combined cycle gas turbine used by Lublin–Wrotków Combined Heat and Power Plant. The model was generated with the GE Energy GateCycle^{TM} software and was based on the parametric design of the real power plant. A brief description of the technology used in the power plant is included in this work. The model was validated by comparing the generated results with the parametric design. The paper finishes with an analysis of the work of the District Water Heater and summary of the most important findings.

Keywords: combined heat and power plant, district water heater, combined cycle gas turbine, mathematical modeling, GateCycle^{TM}

1. Introduction

The model described in this article is an example of commonly used in energy production Combined Cycle Gas Turbine (CCGT). It mainly consists of a Gas Turbine (GT), Heat Recovery Steam Generator (HRSG) and Steam Turbine (ST) [1, 2]. Such power plant is working as a combination of two thermodynamics cycles, i.e., the Brayton cycle and the Rankine cycle, where the Rankine cycle accepts heat rejected by the Brayton cycle. The GT, which is a practical representation of the Brayton Cycle, discharges exhaust gases at a temperature, which is high enough to heat water, and to produce and superheat steam. This part of the CCGT takes place in the HRSG. In order to increase the efficiency of steam production HRSGs are usually designed as a multi pressure heat exchangers (a Multi pressure heat exchanger contains more than one drum). This system is difficult to model due to various restrictions. Fortunately, analysis of the particular restrictions on the modeling of a CCGT has been conducted previously [3]. The HRSG transports heat from high temperature exhaust gases to water/steam. Due to the low heat capacity of exhaust gases and relatively high heat capacity of water, HRSGs are of quite large volumes. A major part of the electrical power is produced in the GT. The power generated by the GT is typically twice that produced in the ST. The steam produced in the HRSG is delivered to the ST, which is a practical representation of the Rankine cycle. Single GT efficiency is too low for energy production as a base unit, as it does not exceed 35%. The CCGT meanwhile reaches an efficiency level of almost 60%, which is impressive compared to conventional coal fired power plants.

2. Software used for simulation

Simulations were performed using General Electric software GateCycle^{TM} [4, 5]. It is an application that can be employed for performance evaluation and design of various thermal power plant systems, such as CCGT, IGCC or coal-fired steam power plant. One example is analysis of different modifications of the AHRTU [6] or thermodynamic optimization of the CCGT [7]. The application enables a wide range of simulation of different states, such as: replacement of particular pieces of equipment for new ones, water injection and changes in the power plant configuration.

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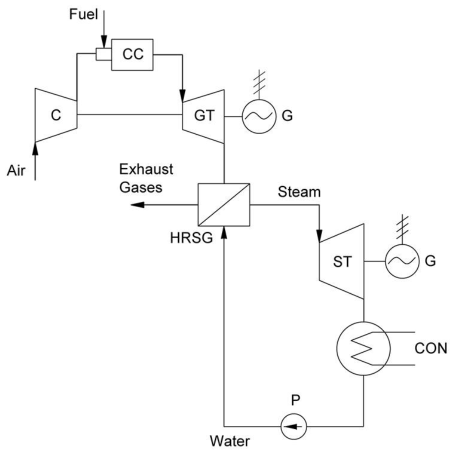

Figure 1: Scheme of a CCGT

In GateCycle^{TM} software there are two basic modes used for calculations: Design Point and Off Design. In the Design Point mode the application optimizes all of the power plant devices, e.g. by calculating heat exchangers' surface areas for given data. Simplifying, it could be assumed that, for any changes in data, GateCycle^{TM} builds a new power plant, where the surface areas of heat exchangers may vary by several orders of magnitude. The method of simulating is entirely different when calculations are run in Off Design mode. Then, data like heat transfer coefficients and surface areas is read from the reference case. This mode is a method of conducting simulation using variable conditions. The properties of each piece of power plant equipment can be obtained from the various reference cases. This enables simulation of a working power plant where several devices were designed for different conditions than the rest.

3. Simulated power plant

3.1. Introduction to the simulated power plant

Lublin–Wrotków Combined Heat and Power Plant, which the calculations were run for, is an example of a CHP plant with a CCGT. It is a division of PGE GiEK S.A and contains one GT, a two-pressure HRSG and an extraction condensing steam turbine that provides heat for the water heating district. The total electrical and thermal power output is 235 MW$_e$ and 185 MW$_{th}$ respectively, of which about 70 MW$_e$ is produced in the ST. The peak thermal power of the whole power plant is provided by four additional water boilers, which results in overall thermal power of 627 MW$_{th}$ [8].

3.2. Description of the model - Design Point [9]

The GT consists of only two elements: the Gas and Data Gas Turbine. The GT was not the most important part of this simulation. It was modeled simply by creating a table of parameters, which are controlled by macros depending on ambient conditions. Element Gas was set to equip the Data Gas Turbine with a model of air at ambient conditions.

The HRSG was developed by modeling heat exchangers separately. The equipment used was as follows: Superheaters, Evaporators, Economizers, Drums, Pipes and Temperature Control Mixer. In order to properly model the HRSG, two drums with separate heat exchangers in their part of the cycle were used. The appropriate values of pressure in both parts of the HRSG were set in the drums. An important issue was correct representation of the first part of economizers for the low- and high-pressure parts. In the simulated power plant the pipes of the economizers cross one another and are simultaneously heated by the exhaust gases. The stream of the exhaust gases was set to equalize their temperatures after the economizers, which would properly represent the situation in an actual plant. The PIPE elements were used to model the live steam pressure drop between the superheaters and the ST.

In order to correctly represent the ST it was divided into four parts. In the first part, the number of control valves was set at 4 and the number of rows in the governing stage was 1. The efficiency of particular parts was calculated using the Spencer/Cotton/Cannon Method, except for the first part where isentropic efficiency was put beforehand. The first two parts represent expansion in the high-pressure part. Before the third part, the steam is mixed with low-pressure live steam from the steam generator. The important issue in this part is extraction of the steam to the deareator. The pressure of the steam was set in the turbine element. The desired mass flow from extraction is demanded by the deareator. After the third part of the turbine extraction of the steam for district heating purposes is modeled. The steam is split into two streams, with one of them going directly to the last, fourth part of the turbine and the other directed to the District Water Heater (DWH). For appropriate modeling of the division of the steam between the low-pressure part of the turbine and DWH the element VALVE was used, where the pressure of the extraction steam is set. Valve is used for simulating the pressure change between turbine stages due to steam extraction for the DWH. After expanding in

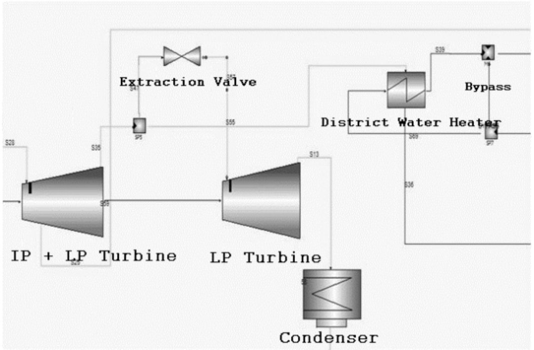

Figure 2: Simulated extraction valve [9]

the low-pressure turbine, the steam is directed to the condenser. The limit values of the steam flow through the low-pressure part of the steam turbine were established, based on the values of the steam pressure at the inlet to this particular part of the turbine. Those limit values were taken from the model data and are equal to 0.7 bar and 0.05 bar, which correspond to 67 kg/s and 5 kg/s respectively. Condenser operating pressure is set directly in this element, which impacts the pressure at the outlet of the low-pressure part of the ST. The water from the condenser is then mixed with the condensed steam from the DWH. After preheating by the water outflow from the deareator, this condensate is directed to the deareator. It is then split into two separate flows and goes to two, high- and low-pressure pumps and thereafter directed precisely to the HRSG.

District water in this particular model is heated by two separate heat exchangers. In the first one, the DWH, heat is delivered by live steam from the extraction of the ST, which is responsible for a major part of the energy delivered to the district water system. The second, called the Recovery Heater (RH) and placed as the last part of the HRSG, is heated by exhaust gases. Water coming back from the district water system is modeled by the Source, whose parameters are clearly defined. From that point the water is separated by the Splitter into two streams, which are directed to the DWH and the RH. To enable control of temperature of water coming out from the DWH, a Bypass of the DWH was modeled. Temperature is controlled by adjusting the appropriate mass flow rate through the Bypass. The RH was designed with a circulation cycle. The main reason for that was to heat up the water coming into the RH in order to decrease the size of the RH. After the heat exchangers, the water streams are mixed in the Mixer and flow out to the district water system, which is modeled by element Sink.

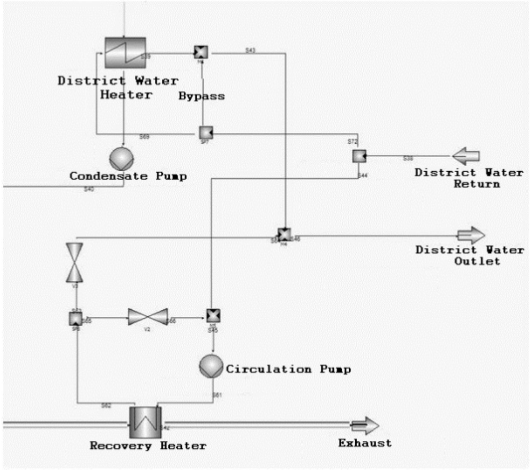

Figure 3: Simulated DWH [9]

3.3. Description of the model - Off Design [9]

The Off Design model is used mostly to simulate the behavior of a particular system in conditions different from the designed in order to assess crucial parameters of that system in variable conditions. The Off Design model used in the discussed object is based on two Design Point models. One was developed for the average temperature occurring in that region in winter -0.9°C and the other for the average temperature in summer, which is 14°C. In order to properly simulate the real CHP, part of the model was taken from the 14°C Design Point model while the rest was taken from 0.9°C Design Point. The low-pressure part of the ST and the Condenser were designed in ambient conditions of 14°C. This is caused by the way in which the size (their mass flow) of elements (e.g. turbine, heat exchangers), based on the parameters of the working medium in GE GateCycle^{TM} software, was designed. In Design Point all of those elements need to be designed for the maximum mass flow rate, at which their power or heat exchange surface will be calculated. The maximum mass flow rate in the discussed system through the last part of the ST occurs during high ambient temperature, which was assumed at an average of 14°C. This is caused by the low demand for steam for the DWH in such conditions. The Condenser and the last part of the turbine were required to be designed for the maximum mass flow rate in order to provide appropriate efficiency of the whole ST Part. On the other hand, the rest of the CCGT was designed for load occurring during lower ambient temperature, i.e. 0.9°C. This optimization for the Off Design model was done due to the higher mass flow rate through the HRSG when there is lower ambient temperature (mass flowing through GT is higher then). In such conditions the amount of steam going through the last part of the turbine is much lower than at 14°C, because a major part of the steam is used for the DWH. Such designed part of the turbine would be too small for the complete Off Design model.

As previously mentioned, GT was modeled by the Data Gas Turbine. It is needed to be mentioned that the Data Gas Turbine always works as an Off Design element. All necessary parameters such as mass flow rate of exhaust gases, power of turbine and temperature of exhaust gases are controlled by appropriate macros.

All of the heat exchangers which form part of the HRSG were set for the Surface Area calculation method. This means that the parameters after the particular heat exchanger are calculated based on the constant surface area of heat transfer, which was assessed in Design Point 0.9°C.

The first three parts of the ST are based on Design Point 0.9°C. The fourth part of the turbine and the condenser are based on Design Point 14°C. The extraction valve was modeled between the third and fourth part of the turbine.

The extraction valve dividing steam into two parts: for the DWH and for the rest of the turbine, is simulated by the Splitter. Steam flow division is regulated by setting the appropriate pressure value at the output of the preceding part of the turbine. This would be manually controlled with the valve by the operator of the CHP in order to adjust the power of the DWH. For easier control of that part macro *Reg_p_zaw_t_wym_ciepl* was developed.

All of those elements are based on the 0.9°C ambient temperature model. The parameters of the water coming back from the district heating system and division of flowing water into two parts (which is directed to the DWH and the RH) are controlled by appropriate macros.

Bypass of the DWH was modeled as a simple combination of Splitter and Mixer elements, allowing one to adjust the temperature after the DWH. Bypass exploitation is especially important for summer load, when the required mass flow rate and temperature for district system is low. In such case low mass flow through the heater causes a temperature increment at the outlet and a simultaneous increase in extraction steam pressure (due to lower cooling). Temperature increment during summer load is undesirable and should be lowered by the remaining water flowing through the DWH's Bypass. In order to enable automatic regulation of the temperature leaving the DWH part, another macro was developed.

To prevent the temperature of exhaust gases from decrement below 85°C, which is the lowest acceptable temperature at the outlet, the option Check for Minimum Gas Exit Temperature was used. Unfortunately, this option works as unreal bypass of the heater, releasing exhaust gases into the atmosphere, right after reaching temperature of 85°C, without further calculations.

3.4. Description of the built model - macros [9]

A macro is a feature of GateCycle^{TM} software that makes it possible to set the values of the parameters in an automatic way. It is done either directly, by giving the desired value of the parameter (Set-type) or indirectly, by changing another parameter value in order to obtain the desired value of the parameter (Control-type). In the discussed model a wide range of macros was used, therefore only the most important ones will be described below.

The first macro to be described is Control-type *Wymiennik_kotlowy*. Its task is to model the circulation cycle near the RH in an appropriate manner. It calculates the amount of water that is required to flow in the cycle in order to heat the water before entering the RH.

The next macros to be described are the ones that deal with the DWH. The first one (Set-type *Wymiennik_cieplowniczy*) sets the Terminal Temperature Difference in the DWH, which is equivalent to setting the temperature at the outlet of the DWH. The second one (Control-type *Wymiennik_cieplowniczy*_2) is used when part of the water omits the DWH. In that situation it controls what fraction of water would pass by the DWH in order to obtain the desired district water temperature. The first macro is used for modeling the winter conditions, whereas the second one is designed to model the summer conditions.

As mentioned earlier, the crucial issue in the HRSG was the correct division of the stream of exhaust gases between the first parts of economizers for the low- and high-pressure parts. That was done by way of the Control-type macro *Temperatura_spalin*. It was tasked with dividing the stream of exhaust gases into two streams in such a way that their temperatures after the economizers would be equal.

Another macro to be described is *Reg_p_zaw_t_wym_ciepl* (Control-type). This one can be used to automatically set the extraction steam pressure in order to achieve the preferred district water temperature.

The next macro is Control-type *Reg_bypass*. It is responsible for simulating the moment when some of the water omits the DWH in order to obtain the desired district water temperature. Then, it is mixed with the water that was heated.

A whole set of macros (Set-type) are used to regulate the cooling and district water parameters. The macros

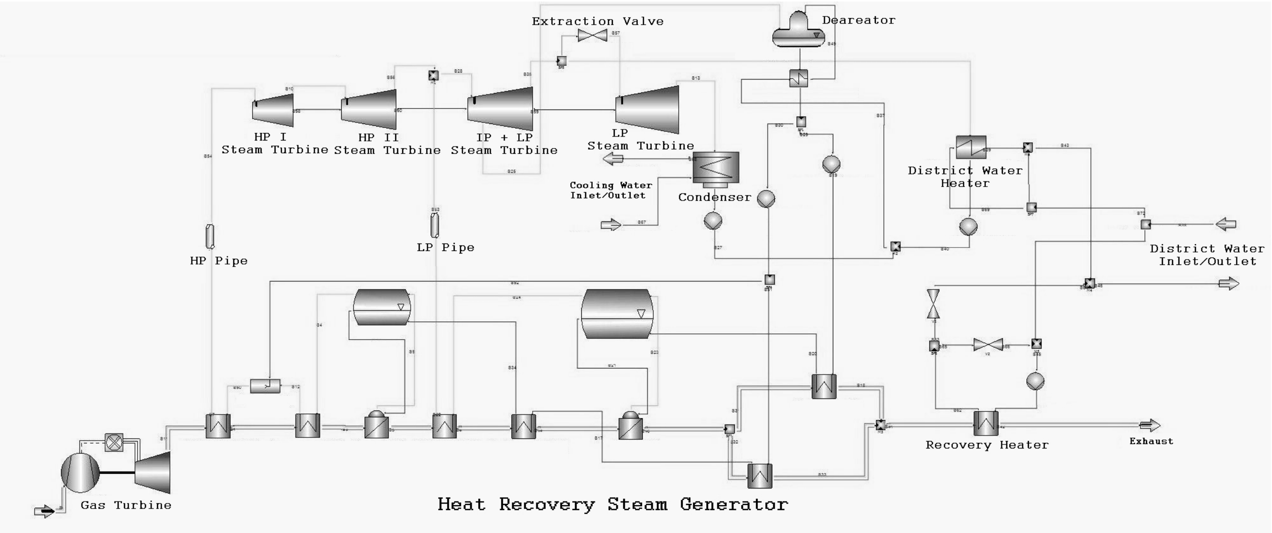

Figure 4: Model of the simulated power plant

Table 1: Comparison for temperatures -20°C and 0.9°C [9, 10]

Ambient Temperature	-20°C		0.9°C		
Data	Model	Reference	Model	Reference	Units
Electrical power of the power plant	233	231.37	239.17	239.15	MW
Electrical power of the GT	173	173	167.6	167.62	MW
Heating power of the power plant	175.07	184.16	149.08	149.97	MW
Power of the DSW	153.86	162.21	130.46	131.09	MW
Power of the RH	21.21	21.95	18.62	18.07	MW

Table 2: Comparison for temperatures 14°C and 30°C [9, 10]

Ambient Temperature	14°C		30°C		
Data	Model	Reference	Model	Reference	Units
Electrical power of the power plant	231.78	232.82	214.32	212.98	MW
Electrical power of the GT	155.52	155.52	139.53	139.54	MW
Heating power of the power plant	40.77	39.72	16.79	16.08	MW
Power of the DSW	23.29	23.37	11.3	11.44	MW
Power of the RH	17.48	16.35	5.49	4.64	MW

deal with their temperatures and mass flows. As mentioned earlier, the GT parameters, such as: power, exhaust gases mass flow and temperature, are set with macros as well. The relations between these parameters and ambient conditions are written down in the tables of parameters.

4. Comparison of obtained data with reference data

In order to check the compatibility of the built model, a comparison was made between the obtained results and the reference data. The built model represents the real power plant with respectable accuracy, as can be seen in Tables 1, 2. The most comparable results are for the ambient temperatures of 0.9°C and 14°C, which can be explained by the fact that the model was based on the reference data for those two temperatures. The great accuracy of the values of electrical power of the gas turbine is a result of the method of modeling it with macros and tables.

5. Analysis of the work of the District Water Heater [9]

The built model was used to determine the behavior of the DWH under variable conditions. The calculations were made using CycleLink utility, which connects GateCycle^{TM} with Microsoft Excel^{TM} software. [5] One of its features is the possibility of conducting a series of calculations with an automatically changing desired parameter. The analysis was divided into two parts due to the different nature of the performance of the DWH in winter and summer conditions. The values of the parameters in the CCGT were the same as in the reference cases.

5.1. Winter conditions analysis

The first set of calculations of the behavior of the DWH were conducted together with changing the pressure of the extraction steam going to the DWH. Three cases were considered: ambient temperature -20°C with 100% load of the GT and 0.9°C with 70% and 100% load. The re-

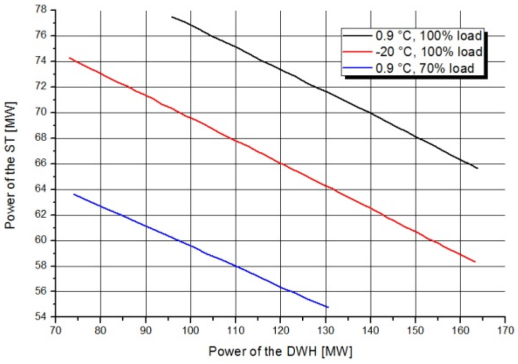

Figure 5: Power of the ST versus power of the DWH

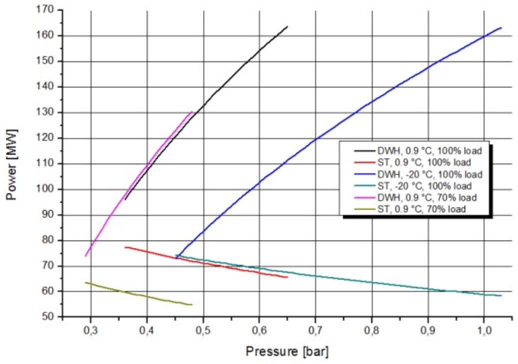

Figure 6: Power of the DWH and ST versus extraction steam pressure

sults are presented in the form of the plots that connect the relations between:

- Electrical power of the ST and the thermal power of the DWH
- Power (thermal of the DWH and electrical of the ST) and extraction steam pressure
- District water temperature after DWH and extraction steam pressure.

From Fig. 5 it can be seen that the relations between electrical and thermal power are approximately linear and parallel for the different CCGT states. As is shown in Fig. 6, increasing the extraction pressure value results in higher values of the thermal power of the DWH and, consequently, lower values of the electrical power of the steam turbine. This is a result of simultaneous processes: decrease of both the steam flow and the enthalpy drop in the low-pressure part of the turbine. The increase in extraction pressure results in an increase in temperature of the district water, as can be observed in Fig 7.

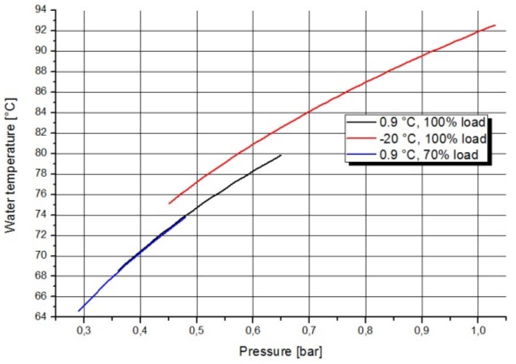

Figure 7: Water temperature after the DWH versus extraction steam pressure

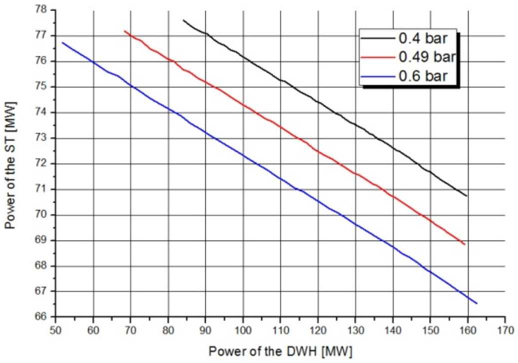

Figure 8: Power of the ST versus power of the DWH

The second set of calculations was done together with varying the water mass flow through the DWH. The calculations were conducted for the ambient temperature 0.9°C (full load of the GT) for the extraction pressures 0.4, 0.49 and 0.6 bar. The results are presented in the form of plots that connect the relations between:

- Electrical power of the ST and thermal power of the DWH
- Power (thermal of the DWH and electrical of the ST) and water mass flow through the DWH
- District water temperature after DWH and water mass flow through the DWH.

Similarly to Fig. 5, in Fig. 8 the relation between the power of the DWH and the ST is linear. In this case the lines for the different pressures are parallel. Another noteworthy detail is that when the increase of the water flow through the DWH occurs, the power of the DWH will increase with simultaneous decrease of the power of the ST

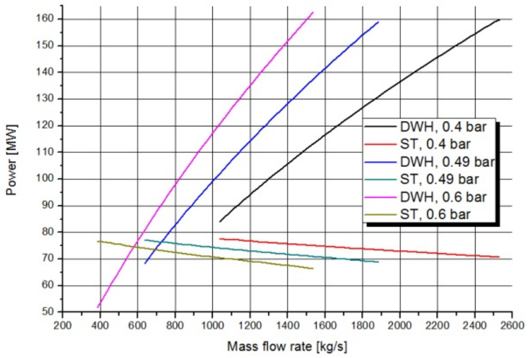

Figure 9: Power of the DWH and ST versus water mass flow rate through the DWH

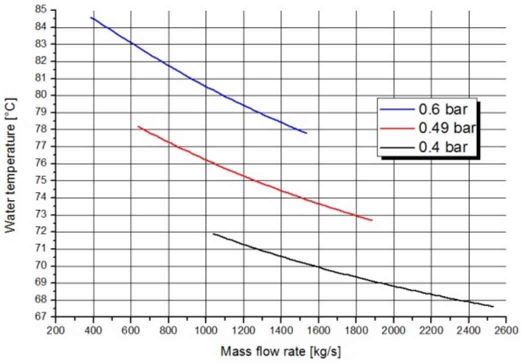

Figure 10: Water temperature after the DWH versus water mass flow rate through the DWH

(Fig. 9). It should be noted that in the previously mentioned plot the extraction pressure does not change when the water mass flow is varied. In the real power plant, that change would imply a subsequent change in pressure. While the power of the DWH will increase, the pressure will be reduced, thus the increase in power will not be so high. Intuitively, the water mass flow increase causes the district water temperature to fall (Fig. 10).

5.2. Summer conditions analysis

Calculations based on the summer conditions were conducted for the following cases: ambient temperature 30°C with 100% load of the GT and 14°C with 70% and 100% load.

Calculations were conducted with variable flow of water through the Bypass and its influence on electrical and thermal power was considered. The results are presented in the form of plots showing the relations between:

- Electrical power of the ST and power of the DWH
- Electrical power of the ST and flow of water through the bypass

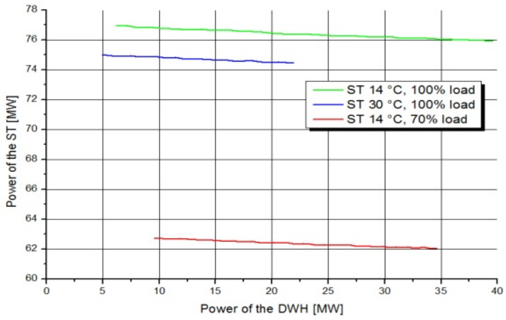

Figure 11: Power of the ST versus power of the DWH

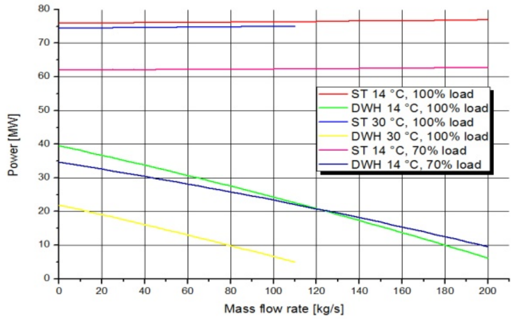

Figure 12: Power of the DWH and ST versus the water mass flow rate through the Bypass

- Power of the DWH and flow of water through the Bypass

As is shown in Fig. 11, there is a linear correlation between the electrical power of the ST and the thermal power of the DWH for variable Bypass mass flow rate. Electrical power decreases slightly as thermal power increases. Fig. 12 shows the behavior of the DWH and steam part together. It can be observed, that when mass flow rate through the Bypass increases electrical power in-

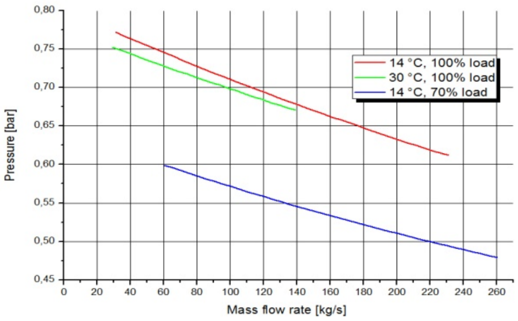

Figure 13: Extraction steam pressure versus mass flow rate through the DWH

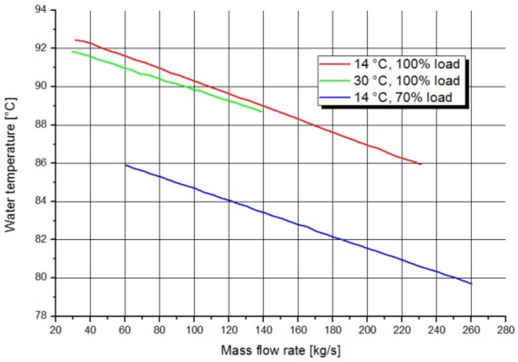

Figure 14: Water temperature after the DWH versus mass flow rate through the DWH

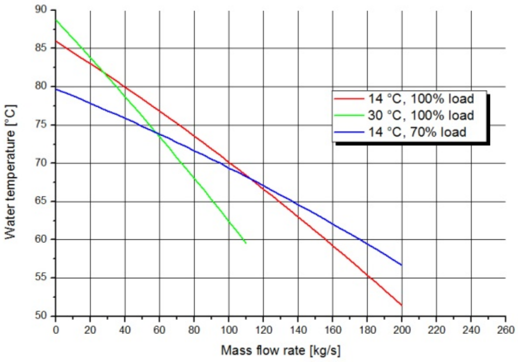

Figure 15: Temperature of the district water after mixing with Bypass water versus mass flow rate through the Bypass

creases slightly, whereas the thermal power of the DWH falls significantly. This is true for real units. It could be explained in the following way: increasing Bypass mass flow rate causes a decrease in DWH mass flow rate. At low DWH mass flow rate, steam cannot be sufficiently cooled by district water and its pressure and temperature increase (see Fig. 13), which results in an increment in the temperature of the DWH's district water outlet and an increment in the steam flow through the last part of the turbine and its power.

The results of district water temperature calculations are presented on plots showing relations between:

- District water temperature directly after DWH and DWH mass flow rate
- District water temperature after mixing with Bypass water and Bypass mass flow rate

The high temperature obtained at the outlet of the DWH is caused by the high steam temperature for low DWH mass flow rate, which is common in summer as the heating system is mainly used for hot tap water. The lower the DWH flow is, the lower the temperature difference is between the inlet of steam and the outlet of district water. This means that such DWH flow would be unable to produce a reasonable water temperature for district heating in summer. An appropriate temperature is obtained after mixing the stream with Bypass water. It should be mentioned that Bypass usage is only reasonable for full opening of the extraction valve (without major pressure loss of the steam directed to the last part of the turbine). The temperature of the steam is directly correlated with its pressure, which directly influences the power of the last part of the turbine.

6. Conclusions [9]

The model of the CCGT is characterized by good compatibility with design parameters and operational data. The results from testing the behavior of the whole unit using variable parameters were considered sufficiently accurate and similar to realistic correlations.

As a result of multiple analysis of the DWH the following statement can be put forward: an increment in the DWH water flow rate will result in an increment in steam usage with a simultaneous reduction in pressure. District water will then be heated to a lower temperature. Due to this effect, there is a need to increase the steam pressure by gradually closing the extraction valve. During summer, for low thermal load, a lower temperature of district water is needed. Due to low DWH water flow, the pressure and temperature of the steam are too high even for a fully open extraction valve. To reduce the water temperature of district water Bypass is used. By regulating the flow through the Bypass one can obtain the requested outlet temperature of the district water. An increment in Bypass flow results in a fall in the power of DWH and a slight increment in electrical power.

Regardless of the quite good compatibility with available data, the model could be upgraded to increase its convergence with the real plant. The main element where major improvements are possible is the GT, as the described model focuses mainly on the steam part of the CCGT, which is the reason why the GT parameters are calculated in macros. A reliable way to simulate the behavior of the GT would be to use correction curves, which are provided by the manufacturer. Another significant improvement could be achieved by refining the developed Design Point with more accurate data and more appropriate calculation methods. The HRSG could also be earmarked for improvement, as the parameters of the HRSG could be more precise and closer to operational data.

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Nomenclature

AHRTU	Air Heat Recovery Turbine Unit
CCGT	Combined Cycle Gas Turbine
CCPP	Combined Cycle Power Plant
CHP	Combined Heat and Power
DWH	District Water Heater
HRSG	Heat Recovery Steam Generator
IGCC	Integrated Gasification Combined Cycle
RH	Recovery Heater
ST	Steam Turbine