ANALYZING OF THERMODYNAMIC PARAMETERS OF 300 MW POWER PLANT IN FOUR DIFFERENT METHODS OF REPOWERING USING GATECYCLE SOFTWARE

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Key words: steam power plant, repowering, supercritical parameters

Summary. In this presented paper the concept of repowering in existing steam cycle power plant was discussed. Mentioned 300 MW steam cycle power plant is located on 1724 m above sea level and equipped with once-through steam boiler with supercritical parameters and powered by natural gas. Using commercial software, four different repowering methods has been simulated on that power plant. There were feed water heating repowering method, hot windbox repowering method, parallel hot windbox repowering method and complete repowering method with maximum supplementary firing. Then thermodynamic analysis of power plant model before and after each repowering method has been investigated. To that end three different gas turbines has been used: Siemens V84.2, ABB GT11N2 and Alstom GT13E2 types. To analyze the models, calculations were performed with two stages: 1) calculation and analyzes of thermodynamic parameters as well as carbon dioxide (CO₂) emissions of the power plant model in mentioned above cases. 2) Calculations of thermodynamic parameters in values 100, 90, 80, 70, 60 and 50 % of the power plant net cycle power in the different cases to show the advantage of different repowering methods behavior in part loads.

1. INTRODUCTION

There are several alternatives to combine and integrate a gas turbine into an existing steam power plant. A choice for one of the repowering options is on one side based on the size and the technical condition of the existing plant (i.e. the remnant life) and on the other side based on the typical needs of the utility [4].

Repowering methods have two categories which are applicable in fossil fuel power plants:
– repowering of nonsolid fuel power plants,
– repowering of solid fuel power plants.

These methods can be divided into two main categories:
– complete repowering (CR),
– partial repowering (PR).

Partial repowering (PR) includes the following methods:
– hot windbox repowering (HWBR),
– feed water heating repowering (FWHR),
– supplementary boiler repowering (SBR) [2].
The repowering options can increase the base plant output typically between 30% to 200%, with heat rate improvements in the 5% to 40% range. The gains that can be realized are primarily a function of the repowering options selected and the size and configuration of the system being repowered [3].

Simplified schematic diagram of repowering concepts of an existing steam power plant is shown on Fig 1.

**Fig. 1.** Simplified schematic diagram of repowering concepts of an existing steam power plant [5]

**Complete repowering (CR)**

Full repowering is defined as complete replacement of the original boiler with a combination of one or more gas turbines (GT) and heat-recovery steam generators (HRSG), and is widely used with very old plants with boilers at the end of their lifetime.

These systems utilize gas turbine exhaust energy to generate steam in a heat recovery steam generator (HRSG), thus displacing the power boiler in the existing steam plant.

It is considered as one of the simplest ways of repowering an existing plant. In most cases repowering projects include the modernization of the steam turbine and I&C.

**Partial repowering**

**Feed water heating repowering (FWHR)**

In a fossil steam plant, approximately 20% to 30% of the throttle steam flow is typically used for feed water heating. If the feed water heating duty was supplied by the gas turbine exhaust energy, then additional steam would be available for passing through the entire length of the...
steam turbine. The gas turbine is used to heat feed water enters the economizer before the feed water enters the boiler. Feed water to the economizer can be taken from the condenser or following any combination of heaters. The greatest improvement in cycle heat rate occurs if all existing feed water heaters re displaced.

**Boiler windbox repowering (HWBR)**

Boiler windbox repowering systems utilize gas turbine exhaust gas as preheated combustion air in the existing boiler. In the application, the hot, oxygen-rich gas turbine exhaust gas provides the function of the forced draft fan and air heater. The heated combustion air reduces the boiler fuel requirements.

Windbox repowering displaces the air pre-heaters and would result in a high stack gas temperature if no modifications of the boiler heat recovery sections were made. In most instances, additional economizer surface will be added to the boiler, transferring this duty from the steam turbine extraction cycle to the boiler, in order to arrive at a reasonable stack gas temperature for the repowered configuration.

**Supplementary boiler repowering (SBR)**

In the supplementary boiler repowering concept the boiler stays in operation for peak and intermediate load. The steam from the boiler is added to the steam from the HRSGs at several pressure levels depending on the condition and capability of the existing steam turbine [5].

In the Table 1 there are shown general characteristics of power plant after repowering in three different methods. It is obvious from the table that the highest capacity and efficiency are available in complete repowering method (CP). But in hot windbox repowering (HWBR) and feed water heating repowering (FWHR) methods the improvement of characteristics is almost similar.


<table>
<thead>
<tr>
<th></th>
<th>HWBR</th>
<th>FWHR</th>
<th>CR</th>
<th>GT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacity increase (%)</strong></td>
<td>15-30</td>
<td>10-30</td>
<td>160-200</td>
<td>-</td>
</tr>
<tr>
<td><strong>Efficiency improvement (%)</strong></td>
<td>3-6</td>
<td>2-5</td>
<td>Up to 12</td>
<td>-</td>
</tr>
<tr>
<td><strong>NOx decrease (%)</strong></td>
<td>50-80</td>
<td>10-20</td>
<td>50-80</td>
<td>-</td>
</tr>
<tr>
<td><strong>Limitation factor (s)</strong></td>
<td>Existing boiler</td>
<td>Steam turbine (s)</td>
<td>Existing condenser and steam turbine (s)</td>
<td>-</td>
</tr>
<tr>
<td><strong>Special advantage</strong></td>
<td>Heat rate improvement up to 10-15%</td>
<td>Heat rate improvement 5-10%</td>
<td>Heat rate improvement up to 30-40%</td>
<td>-</td>
</tr>
<tr>
<td><strong>Outage time</strong></td>
<td>8</td>
<td>2</td>
<td>12-18</td>
<td>10-12</td>
</tr>
<tr>
<td><strong>Gas turbine capacity</strong></td>
<td>Up to 30% of existing steam turbine capacity</td>
<td>Up to 20% of existing steam turbine capacity</td>
<td>160-200% of existing steam turbine capacity</td>
<td>-</td>
</tr>
</tbody>
</table>
Also it is a fact that complete repowering method with maximum supplementary firing can achieve higher characteristics compared to without maximum supplementary firing.

The maximum firing rate is set by the oxygen content of the gas turbine exhaust. With this type of steam generator, the exhaust from the gas turbine is used primarily as an oxygen carrier. The heat content of the gas turbine exhaust is low compared with the heat input of firing in the boiler. The design of a steam generator of this type is practically identical to that of a conventional boiler with a furnace, except that there is no regenerative air pre-heater. The gas turbine exhaust has a temperature of 450 to 650°C, rendering a regenerative heater unnecessary. To cool the exhaust to a sufficiently low temperature downstream of the steam generator, an additional economizer is provided, which takes over a portion of the feed water preheating from the regenerative preheating of the steam turbine. The best arrangement splits the feed water between the economizer and the high-pressure feed heaters. When the fuel is gas, an additional low-pressure partial flow economizer improves efficiency. The fuel combusted in the boiler may be oil, gas, or pulverized coal. This application can be used to increase the output from an existing conventional steam turbine plant using a gas turbine and its exhaust energy [6].

2. SOFTWARE USED FOR SIMULATION

Mathematical models can be used to establish the characteristics of the object, as well as the technical and economic optimization. For this purpose commercial General Electric software GateCycle [7] is used for design and performance evaluation of thermal power plant system at both design and off-design points.

A GateCycle™ model represents a specific plant or equipment configuration. In design mode, the required performance attributes can be specified. The software then calculates (“sizes”) the equipment to match these performance criteria. In off-design mode, the software works in the other direction: the operational conditions can be defined, and the GateCycle™ application calculates the corresponding “as-built” performance. GateCycle™ models are extremely flexible, allowing an indefinite number of calculation cases to cover variations in design parameters as well as plant performance under “off-design” conditions [7].

Also, there is library with more than 100 gas turbines along with saved correction curves. This allows mathematical modeling of the power plant (gas turbine) to determine performance for conditions other than ISO or for variable load without the need for detailed data from vendor.

In this paper three types of gas turbines have been used: Siemens V84.2, ABB GT11N2 and Alstom GT13E2. First two chosen gas turbines were applied using the GateCycl library. The third one was created by details manually.
3. DESCRIPTION OF THE POWER PLANT MODEL BEFORE REPOWERING AND AFTER REPOWERING (DESIGN POINT)

Presented here simulated power plant is an example of 300 MW steam cycle power plant with supercritical parameters powered by natural gas. The parameters and relevant calculations were close to the existing power plant in Armenia. That is, in the first the available the old steam cycle power plant and then in the result of re-powering, added gas turbine(s).

Steam cycle power plant is located on 1724 m above sea level and consists of ТГМП-344 АС once-trough steam boiler with supercritical parameters and K-300-240 steam turbine. These two main equipments are Russian production.

The reference values for ambient conditions and fuel parameters are presented in Table 2.

Table 2 Reference values for ambient conditions and fuel parameters for steam boiler and GT

<table>
<thead>
<tr>
<th>Ambient conditions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative humidity - 60 %</td>
</tr>
<tr>
<td>Ambient pressure - 0.822 bar</td>
</tr>
<tr>
<td>Ambient temperature - 15 °C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel conditions for steam boiler:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel pressure - 1.72 bar</td>
</tr>
<tr>
<td>Fuel temperature - 15.5 °C</td>
</tr>
<tr>
<td>Fuel Gas Lower Heating Value (LHV) - 45096 kJ/kg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel conditions for added gas turbine(s):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel pressure - 25.5 bar</td>
</tr>
<tr>
<td>Fuel temperature - 50 °C</td>
</tr>
<tr>
<td>Fuel Gas Lower Heating Value (LHV) - 45096 kJ/kg</td>
</tr>
</tbody>
</table>

All reference values correspond to the design parameters of real power plant

In the paper there are presented four repowering methods:

- feed water heating repowering,
- hot windbox repowering,
- parallel hot windbox repowering,
- complete repowering with maximum supplementary firing.

Actually the chosen repowering method for existing steam cycle power plant is parallel hot windbox repowering. It means that the old steam boiler of power plant has not been removed, but has been modified. Also on the same steam cycle power plant other three different repowering methods have been analyzed. But there is a very interesting fact that in case of
complete repowering method with maximum supplementary firing steam generator the results are very close to characteristics of parallel hot windbox repowering method.

And know more detailed about every selected method.

3.1. Steam cycle power plant before repowering

In Figure 2 there is presented the model diagram of simulated power plant before repowering.

Boiler part was developed by modeling fossil boiler and heat exchangers separately. The equipment was used as follows: fossil boiler, high pressure super heater (HPSH), intermediate pressure super heater (IPSH), economizer (ECON). There were also installed splitters, pipes and mixers. The air is supplied to the boiler through two ducts: primary air duct and secondary air duct. The parameters of the considered fossil boiler correspond to the design parameters of real power plant. In the Table 3 the design parameters of steam boiler were shown.

<table>
<thead>
<tr>
<th>Table 3 Design general parameters of steam boiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live steam pressure</td>
</tr>
<tr>
<td>Live steam temperature</td>
</tr>
<tr>
<td>Steam generating capacity</td>
</tr>
<tr>
<td>Secondary steam pressure</td>
</tr>
<tr>
<td>Secondary steam temperature</td>
</tr>
<tr>
<td>Natural gas mass flow</td>
</tr>
</tbody>
</table>

The steam turbine (ST) consists of three parts: high-pressure part (HPST), intermediate-pressure part (IPST) and low-pressure part (LPST). The efficiency of particular parts was calculated using the Design Efficiency Method and the Isentropic Expansion Efficiency was equal to 0.9 for all parts.

The inlet steam pressure for all parts of steam turbine was calculated using the Design Pressure Method. For high pressure part the inlet pressure was fixed 240 bar but for next two parts was calculated automatically. These all calculation methods are available in GateCycle software.

Steam turbine part was equipped with regeneration system, which consists of seven feed water heaters (FWH) and deaerator (DA). Three FWH from seven were installed in the high pressure part of feed water and four of them - in the low pressure part. Feed water heaters low pressure part was divided into two sections with individual pumps: the first stage condensate pump (CP1) with FWH1 and FWH2 and the second stage condensate pump (CP2) with FWH3 and FWH4.
Fig. 2. Model diagram of simulated power plant Before Repowering (BR): HPST - high pressure steam turbine, IPST - intermediate pressure steam turbine, LPST - low pressure steam turbine, GEN – electrical generator, COND – condenser, CP1; 2 - condensate pump 1; 2, MIX - mixer, FWH1;2;3;4;6;7;8 - feed water heaters №1;2;3;4;5;6;7;8, DEAER - deaerator, FWP - feed water pump, SP1;2- splitter №1;2, ECON - economizer, HPSH - high pressure super heater, IPSH - intermediate pressure super heater, V1 - control valve, GAS - boiler input fuel, AIR - boiler incoming air, EXH - boiler exhaust gases

3.2. Combined cycle power plant (CCPP) in the result of feed water heating repowering (FWHR)

In this case Siemens V84.2 gas turbine with 87.7 MW has been added in the steam cycle power plant. Then in the boiler section, after economizer, there were installed additional water gas heat exchangers (with high and low pressure) parallel with steam turbine regeneration system to use the temperature of added gas turbine exhaust gas. The design parameters of selected GT are presented in Table 4.

Table 4 Design parameters of Siemens V84.2 gas turbine

<table>
<thead>
<tr>
<th>Design parameters of Siemens V84.2 gas turbine</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhaust gases mass flow</td>
<td>kg/s</td>
<td>290</td>
</tr>
<tr>
<td>Exhaust gases temperature</td>
<td>°C</td>
<td>552</td>
</tr>
<tr>
<td>Net electric power</td>
<td>MW</td>
<td>87.5</td>
</tr>
<tr>
<td>Efficiency</td>
<td>%</td>
<td>33.52</td>
</tr>
<tr>
<td>O₂ mole fraction</td>
<td>-</td>
<td>0.1332</td>
</tr>
</tbody>
</table>
The type of gas turbine has been selected from Gatecycle GT library based on the optimal distribution of feed water mass flow through feed water heaters and added gas water heat exchangers. Also one of feed water heaters in high pressure part of regeneration system (FWH8) has been removed to reach the optimal value of feed water distribution as mentioned above. The model diagram of simulated power plant after feed water heating repowering (FWHR) is presented in Figure 3.

**Fig. 3.** Model diagram of simulated power plant After Feed Water Heating Repowering (FWHR): HPST - high pressure steam turbine, IPST - intermediate pressure steam turbine, LPST - low pressure steam turbine, GEN1;2 - gas turbine and steam turbine electrical generators, COND – condenser, CP1;2 - condensate pump 1;2, MIX1;2;3 - mixer №1;2;3, FWH1;2;3;4;6;7 - feed water heaters №1;2;3;4;5;6;7, DEAER - deaerator, FWP - feed water pump, SP1;2;3;4 - splitter №1;2;3;4, ECON - economizer, HPSH - high pressure super heater, IPSH - intermediate pressure super heater, GWHE – gas water heat exchanger, V1 - control valve, GAS1;2 - gas turbine and boiler input fuel, AIR1;2 - gas turbine and boiler input air, EXH1;2 - gas turbine and boiler exhaust gases

### 3.3. CCPP in the result of hot windbox repowering (HWBR)

In this case ABB GT11N2 gas turbine with 95.4 MW has been added in existing steam cycle power plant. Based on the fraction of oxygen within exhaust gases, the gas turbine was chosen from Gatecycle GT Library. The volume of oxygen within exhaust gases must be correspond oxygen consumption by fossil boiler. Then any changing in the scheme of existing steam cycle power plant has not been done. The design parameters of selected GT are presented in
Table 5 and the model diagram of simulated power plant after hot windbox repowering is presented in Figure 4 accordingly.

**Fig. 4.** Model diagram of simulated power plant After Hot Windbox Repowering (HWBR): HPST - high pressure steam turbine, IPST - intermediate pressure steam turbine, LPST - low pressure steam turbine, GEN1;2 - gas turbine and steam turbine electrical generators, COND – condenser, CP1;2 - condensate pump 1;2, MIX - mixer, FWH1;2;3;4;6;7;8 - feed water heaters №1;2;3;4;5;6;7;8, DEAER - deaerator, FWP - feed water pump, SP1;2 - splitter №1;2, ECON - economizer, HPSH - high pressure super heater, IPSH - intermediate pressure super heater, V1 - control valve, GAS1;2 - gas turbine and boiler input fuel, AIR1;2 - gas turbine and boiler input air, EXH - boiler exhaust gases

**Table 5** Design parameters of ABB GT11N2 gas turbine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhaust gases mass flow</td>
<td>kg/s</td>
<td>300</td>
</tr>
<tr>
<td>Exhaust gases temperature</td>
<td>°C</td>
<td>532</td>
</tr>
<tr>
<td>Net electric power</td>
<td>MW</td>
<td>95.4</td>
</tr>
<tr>
<td>Efficiency</td>
<td>%</td>
<td>35.22</td>
</tr>
<tr>
<td>O₂ mole fraction</td>
<td></td>
<td>0.1335</td>
</tr>
</tbody>
</table>
3.4. CCPP in the result of Parallel hot windbox repowering (PHWR)

Alstom GT13E2 gas turbine with 140 MW has been added in existing steam cycle power plant in this case. This variant is actually used now in real power plant in Armenia. This is the combination of two previews methods: feed water heating repowering and hot windbox repowering. Design parameters of the gas turbine are mentioned above in Table 6.

Table 6  Design parameters of Alstom GT13E2 gas turbine

<table>
<thead>
<tr>
<th>Design parameters of Alstom GT13E2 gas turbine</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhaust gases mass flow</td>
<td>kg/s</td>
<td>450</td>
</tr>
<tr>
<td>Exhaust gases temperature</td>
<td>°C</td>
<td>516</td>
</tr>
<tr>
<td>Heat rate (LHV)/Effect</td>
<td>kJ/kW-s</td>
<td>2.8386</td>
</tr>
<tr>
<td>Net electric power</td>
<td>MW</td>
<td>139.6</td>
</tr>
<tr>
<td>Efficiency</td>
<td>%</td>
<td>35.72</td>
</tr>
<tr>
<td>O₂ mole fraction</td>
<td>-</td>
<td>0.1396</td>
</tr>
</tbody>
</table>

The gas turbine was created part by part without using Gatecycle GT Library in comparison with previews cases. The GT exhaust gas duct was connected to the boiler burners and supply oxygen for burning process. In steam cycle regime air is supplied to the boiler through two ducts: primary air duct and secondary air duct. But in combined cycle regime those ducts were closed, because the oxygen quantity within GT exhaust gas is enough for burning process in the boiler. Also there is installed a splitter (SP5) which regulate the oxygen quantity entering to the boiler duct burners. Moreover as in the previews version gas water heat exchangers are installed parallel with steam turbine regeneration system in high and low pressure parts. Also one of feed water heaters in high pressure part of regeneration system (FWH8) has been removed to reach the optimal value of feed water distribution of feed water mass flow through feed water heaters and added gas water heat exchangers. The model diagram of simulated power plant after parallel hot windbox repowering (PHWR) is shown in Figure 5.
3.5. CCPP in the result of complete repowering with supplementary firing method

In this method also added the same Alstom GT13E2 gas turbine but the old steam boiler is replaced completely with heat recovery steam generator (HRSG). But the components of the HRSG are close to the previews boiler or real power plant steam boiler components with their design and function. That is, HRSG part was developed by modelling once-through boiler and heat exchangers separately. The equipment used was as follows: Once-through boiler, high pressure super-heater, intermediate pressure super-heater, economizer, high pressure gas water heat exchanger and low pressure gas water heat exchanger. Also there was installed a duct burner (DB), which was used before once-through boiler for maximum supplementary firing. Moreover, there was installed additional gas element (GAS2) to supply the duct burner. In Inputs section the temperature after duct burner is resulting from incoming fuel flow. Once-through boiler was calculated through desired steam production inputs. Steam turbine regeneration system is the same as in previews version of repowering, i.e. the FWH8 has been removed and gas water heat exchangers were installed parallel with steam turbine regeneration system. In Figure 6 the model diagram of power plant after complete repowering was illustrated.

4. CALCULATIONS AND ANALYZES (OFF- DESIGN MODE)

In general the off design mode is used mostly to simulate the behavior of a particular system in conditions different from the designed in order to access crucial parameters of that system in variable conditions. In this section in off-design mode analyzes and calculation results of thermodynamic parameters of the model are presented. Analyzes and calculation have been done in the different cases as mentioned in previews section:

- Before repowering,
- After feed water heating repowering,
- After hot windbox repowering,
- After complete repowering with maximum supplementary firing,
- After parallel hot windbox repowering.

The simulations were performed with two stages:

1) Calculation and analyzes of thermodynamic parameters as well as carbon dioxide (CO₂) emissions of the power plant model in mentioned above cases.

2) Calculations of thermodynamic parameters in values 100, 90, 80, 70, 60 and 50 % of the power plant net cycle power in the different cases to show the advantage of different repowering methods behavior in part loads.

Stage one: In this part thermodynamic parameters of the power plant model before and after different cases of repowering were analyzed and then as a result were made charts, which
describe the effect of each repowering method. Also carbon dioxide (CO\textsubscript{2}) emissions were calculated before and after each repowering methods.

GT, steam cycle and combined cycle net electrical power were illustrated in Figure 7. According to the chart the net steam cycle power is on the same level in all presented cases (~300MW). Actually that index is increased after repowering. But because of limited resources (equipment) of power plant, steam turbine power was fixed ~300 MW, decreasing the mass flow of natural gas providing to the steam boiler. This variant gives an opportunity to avoid installing new electrical generator of steam turbine and also changing the design of already existing equipment of power plant. According to the chart the highest amount of net cycle electrical power of combined cycle power plant is available in complete repowering with MSF and parallel hot windbox repowering methods and it is equal to 440.28 and 440.64 accordingly.

In Figure 8 net cycle efficiency and net cycle heat rate improvement were presented. According to the chart first two methods - feed water heating repowering and hot windbox repowering have about the same effect, 5.34 % and 6.15 % net cycle efficiency improvement respectively. But in the next two methods the improvement rate is more valuable - 10.33 % in complete repowering with MSF and 10.44% in parallel hot windbox repowering. The variation of improvement of net cycle efficiency is from 36.62 to ~ 47.00 %.
In the next figure (Fig. 9) there were presented the rate of increase in CO₂ emission in net cycle exhaust gases and the rate of decrease in CO₂ in net cycle exhaust gases for per MW electrical power. It is an interesting fact that although the fraction of CO₂ was increased after repowering CO₂ emissions in boiler exhaust gases per megawatt power was decreased. This finding may indicate that it is possible to increase the installed capacity with reducing the pollutants emissions by hot windbox repowering of thermal power plants. According to the chart carbon dioxide emission in net cycle exhaust gases for per MW electrical power was decreased the most in complete repowering with maximum supplementary firing and it was equal to 25.71%, although the emission in exhaust gases was increased after any kind of repowering. In fact this is one of ideal solutions of global ecological problem, especially for coal fired power plants.
In Figure 10 two important characteristics were illustrated, which can be interesting by economical side. There are rate of increase in net cycle total electrical power and rate of decrease in fuel total mass flow for net cycle per MW electrical power. According to calculation because of complete repowering with maximum supplementary firing and parallel hot windbox repowering total electrical power of net cycle was increased by 46.49% and after parallel hot windbox repowering the same index was increased 46.61% comparing with steam cycle power plant electrical power before repowering. In the same time fuel total mass flow for net cycle per MW electrical power was decreased by 23.71 % and 23.77% after in above mentioned above repowering methods correspondingly.

![Figure 10](image)

**Fig. 10.** Variation of net cycle total power and fuel total mass flow for net cycle per MW electrical power in different repowering methods

Stage two: In the second part of analyzes there were changed net cycle total electrical load from 100% to 50% to establish the advantage of each repowering method in part loads. In decreasing process of power plant net cycle total electrical load, gas turbine behavior is different in each repowering method. For example, in feed water heating repowering method, after decreasing electrical load below from 70%, gas turbine load have to be changed. In complete repowering method with maximum supplementary firing, the behavior of GT is about the same. That is, after decreasing of total net cycle electrical power below 60%, GT load is changing. But in hot windbox repowering and parallel hot windbox repowering methods GT electrical load practically has not been changed. Changing electrical load of steam turbine has been realized through changing the providing fuel mass flow to the steam boiler. But to change gas turbine electrical load the amount of electrical power inputted in GT input section.
In the Figure 11 there were shown the variation of steam turbine power before repowering, as well as combined cycle power plant total power after different repowering methods depending on live steam mass flow in part loads.

The largest variation of combined cycle power plant power was available in feed water heating repowering method, from 387.7 MW to 224.7 MW and within this range live steam mass flow variation was from 219.8 kg/s to 108.2 kg/s. This fact is because of the selected gas turbine type and also the variant of combination of GT in steam cycle. The variation in this method is close to variation of steam cycle power plant electrical power variation in part load. But in three other methods this variation is different. The general range of live steam mass flow variation for other three different repowering methods was varied from 260 kg/s to 140 kg/s.

In the last plot (Figure 11) there was shown net cycle efficiency (%) variation in part loads before and after repowering. The highest efficiency was available in 60% load of total net cycle electrical power in complete repowering method with maximum supplementary firing, and was equal to 51.74 %. In that case live steam mass flow is equal to 183.66 kg/s. In general, in part-load regimes of combined cycle power plants the net cycle efficiency is higher than in nominal load. It means during part-load regimes the heat of exhaust gases coming from GT can compensate heat balance when the mass flow of fuel at the inlet of steam boiler burner was decreased. But in case of steam cycle power plants there is the opposite situation. Such types of power plants have low efficiency in part-loads. In this case steam cycle power plant efficiency before repowering was varied from 36.62 % to 33.39 %, but in the same time, for example, after parallel hot windbox repowering the net cycle efficiency of the same power plant is reached from 47.04 % to 50.73 % in part-load regimes.

![Variation of net cycle total electrical power in part loads](image-url)
Also there is another fact. In complete repowering method with MSF and in feed water heating repowering method the value of net cycle efficiency is growing till that time when gas turbine is working with nominal load. And when GT is working in part-load regimes this value is going down. Concretely this fact is available below from 60% of net cycle electrical power load in complete repowering method and below from 70% of the same value in feed water heating repowering method.

![Diagram](image)

**Fig. 11.** Net cycle efficiency variation depending live steam mass flow in part loads

## 5. CONCLUSIONS

The results showed that the total generating electrical power of CCPP after parallel hot windbox repowering and complete repowering with MSF was increased by 46.61 % and 46.49 % accordingly. The highest net cycle efficiency was available in parallel hot windbox repowering method and it was equal to 47.04 %, increased by 10.44 %. In spite of the fact that the same effect was available in complete repowering method with MSF (the values are almost similar), the author is inclined to select parallel hot windbox repowering method as the best one. There was another advantage that CO\(_2\) emissions in boiler exhaust gases for per megawatt power decreased by 23.22 %. Also the fuel total mass flow providing to the steam boiler was decreased by 23.77 % in mentioned repowering method.

In part-loads the largest variation of combined cycle power plant power was available in feed water heating repowering method, from 387.7 MW to 224.7 MW and within this range live steam mass flow variation was from 219.8 kg/s to 108.2 kg/s. But in three other methods this variation is different. The general range of live steam mass flow variation for other three
different repowering methods was varied from 260 kg/s to 140 kg/s. The highest efficiency was available in 60% load of total net cycle electrical power in complete repowering method with maximum supplementary firing, and was equal to 51.74%. In that case live steam mass flow is equal to 183.66 kg/s. In that case steam cycle power plant efficiency before repowering was varied from 36.62 % to 33.39 %, but in the same time, after parallel hot windbox repowering the net cycle efficiency of the same power plant is reached from 47.04 % to 50.73% in part-load regimes.

The scope of the paper was to show the effect of different kinds of repowering. All design parameters corresponded to the real power plant parameters nowadays and in the near future there is planned to reach more research results and use this theme in author’s doctoral research work.

LITERATURE


Słowa kluczowe: siłownia parowa, modernizacja, parametry nadkrytyczne

Streszczenie. W artykule została przedstawiona koncepcja modernizacji istniejącego układu siłowni parowej. Siłownia ta zlokalizowana jest na wysokości 1724 m nad poziomem morza. Siłownia generuje moc 300 MW, wyposażona jest w kocioł przepływowy na parametry nadkrytyczne i zasilana jest gazem ziemnym. Wykorzystując komercyjne środowisko numeryczne została przeprowadzona symulacja czterech wariantów modernizacji siłowni. Poszczególne warianty to podgrzew wody zasilającej, metoda „hot windbox”, metoda „parallel hot windbox” oraz zastąpienie kotła gazowego turbiną gazową. Została wykonana analiza termodynamiczna przed modernizacją oraz po zastosowaniu każdej z metod. Przeanalizowano zastosowanie trzech różnych turbin gazowych: Siemens V84.2, ABB GT11N2 oraz Alstom GT13E2. W celu przeanalizowania wariantów obliczenia przeprowadzono w dwóch krokach: 1) Obliczenia i analiza termodynamiczna parametrów pracy siłowni oraz emisji dwutlenku węgla dla rozważanych wariantów. 2) Obliczenia parametrów termodynamicznych dla różnego obciążenia układu siłowni, tj. 100, 90, 80, 70, 60 oraz 50% mocy w celu zaprezentowania zachowania różnych metod modernizacji w zakresie obciążeń częściowych.

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