Analysis of the dual-fuel combined cycle power plants with a parallel operating scheme efficiency

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Abstract. The article addresses the problems of local power plants operating on fossil fuels such as gas and coal. As a solution to the problem, it is proposed to consider dual-fuel combined cycle power plants with a parallel operating scheme. This type of combined cycle technology is good variant for integration into coal predominating districts. Therefore, the efficiency of dual-fuel combined cycle power plants operating at subcritical ($p_0 = 13$ MPa, $t_0 = 540 \degree C$) and supercritical ($p_0 = 24$ MPa, $t_0 = 545 \degree C$) initial steam parameters are discussed in the article. The thermal model and a calculation methodology for the installation under consideration are proposed. The results of the installation’s technical and economic indicators analysis are presented. Additionally article sets out the assessment of capital costs, Net Present Value and the possibility of using the technology under study within the framework of the considering region.

1. Introduction

Nowadays a significant part of electricity (~ 65%) in Russia is generated at thermal power plants operating on fossil fuels (gas, coal). The main problem of such stations is the low efficiency of electric power generation, which is ~ 28 – 34 % [1]. The reason for such a low electricity generation efficiency is the equipment’s depreciation (due to the fact that projected service life of the equipment has been repeatedly extended) [2], the obsolescence of the equipment (most of the power plants are operated at subcritical steam parameters) [3], as well as a low percentage of implementation units using advanced technologies such as combined cycle gas turbine units (CCGT) [4]. Thus, increasing the efficiency of electric power generation is one of the key directions in the development of energy not only in Russia but also in the world [5].

The trend of recent years shows that combined-cycle power units that use natural gas as the main fuel are being implemented in many regions of the country. [6] However, for regions where coal predominates in the territorial fuel balance, for example, Siberian Federal District, Ural Federal District, Far Eastern Federal District (Figure 1), the CCGT using is not even considered. [7] One of the variant for integration coal into combined cycle technologies can be dual-fuel CCGT [8].

Thus, it is relevant to study dual-fuel combined-cycle power plants with a parallel scheme of work [9] with the designing of the scheme and calculation methodology for the technology under consideration. In addition it is also interesting to analyze the plant’s operation with different initial parameters of steam [10] and to estimate capital costs.
2. Materials and Methods
Let us consider the operation principle and calculation methodology of the technology under consideration [11].

2.1. Operation principle and thermal model
The analytical thermal model of the installation is shown in Figure 2.

Figure 1. Fuel balance of the coal predominate Districts.

Figure 2. Example of CCPP analytical thermal model: GTU – gas turbine unit; STU – steam turbine unit; SG – steam generator of waste-heat recovery unit; HHE, LHE – heat ex-changers of high and low pressure; SB – steam boiler; P1, P2 – high-pressure preheaters; P3, P4, P5, P6 – low-pressure preheaters; D – deaerator; C – condenser; CP, FWP – condenser and feed water pump; PRDS – pressure-reducing desuperheating station; NGTU, NSTU – electrical output of gas and steam turbine unit.
Gas is supplied to the combustion chamber (CH) of the gas turbine unit (GTU), due to its combustion, electric energy is generated in a part of the gas turbine unit. The gases exhausted in the GTU are sent to the waste heat boiler (WHB) that consists of steam-generator block, where a part of the steam which is subsequently combined with the main steam flow of the steam turbine unit is generated, and two heat exchangers (high and low pressure) for heating the feed water. The steam turbine unit (STU) consists of a steam turbine with an electric generator, a regeneration system, and a steam boiler fueled by coal. Thus, the plant burns two types of fuel: gas and coal. The parallelism of work involves dividing the feed water flow, which is heated and generated into steam in the part of the STU and GTU and after this it is combined in the part of the steam turbine unit.

2.2. Calculation methodology
Combined cycle power plants calculation methodology consists of steps are described below.

2.2.1. Gas turbine unit calculation.

Determination of parameters at the main points of the Brayton cycle, calculation of specific work \(l\), \(\text{kJ/kg}\), determination of efficiency \((\eta_{\text{GTU}})\) and equivalent fuel consumption of a GTU \((b_{\text{GTU}}, \text{KgCE./kilowatt-hour})\):

\[
l = (T_0 - T_k) - (T_1 - T_c)
\]

\[
\eta_{\text{GTU}} = \frac{l}{(T_0 - T_i)\eta_{\text{EM}}}
\]

\[
b_{\text{GTU}} = 0.123 \frac{\eta_{\text{GTU}}}{\eta_{\text{GTU}}}
\]

where:
- \(T_0\) – temperature of gases after combustion chamber, K;
- \(T_k\) – temperature after GTU, K;
- \(T_i\) – compressed air temperature behind the compressor, K;
- \(T_c\) – ambient temperature, K;
- \(\eta_{\text{EM}}\) – electromechanical losses.

2.2.2. Steam turbine unit calculation.

Determination of parameters at characteristic points of the steam expansion process, calculation of steam flow condition per turbine \((G_0, \text{Kg/s})\), efficiency \((\eta_{\text{STU}})\), equivalent fuel consumption \((b_{\text{STU}}, \text{KgCE./kilowatt-hour})\):

\[
G_0 = \frac{k_c N_{\text{STU}} 10^3}{H_0 \eta_w}
\]

\[
\eta_{\text{STU}} = \eta_c \eta_{\text{SAT}} \eta_a \eta_{\text{EM}}
\]

\[
b_{\text{STU}} = 0.123 \frac{\eta_{\text{STU}}}{\eta_{\text{STU}}}
\]

where:
- \(k_c\) – correction index for steam flow condition per turbine;
2.2.3. Waste heat boiler and steam boiler calculation.

Determination of the amount of heat transferred to each heat-delivery surface \( Q_i, \) kW, and it’s area \( F_i, \) m²:

\[
Q_i = c_p G_i \Delta t
\]

\[
F_i = \frac{10^3 Q_i}{k \Delta t}
\]

where:
- \( c_p \) – heat capacity at constant pressure, kJ/kg;
- \( G_i \) – steam/gas flow, Kg/s;
- \( \Delta t \) – temperature difference, K;
- \( k \) – heat-transfer coefficient, W/(m²K).

2.2.4. Layout and calculation of the thermal circuit in the autonomy mode and in the CCGT mode.

Determination of the installation efficiency \( \eta_{CCPP} \):

\[
\eta_{CCPP} = \frac{N_{GTU} \eta_{BOP}^{STU} + N_{STU} \eta_{BOP}^{STU}}{N_{GTU} \frac{0.123}{3.6 \eta_{GTU}} + N_{STU} \frac{0.123}{3.6 \eta_{STU}}} 29.3 - Q_{WHB}
\]

where:
- \( N_{GTU}, N_{STU} \) – electrical output of gas and steam turbine unit consequently, kW;
- \( \eta_{BOP}^{GTU}, \eta_{BOP}^{STU} \) – balance of plant needs efficiency;
- \( Q_{WHB} \) – waste heat boiler supplied heat, kW.

2.3. Capital costs and the payback period

Together with technical and economic indicators another important factor in assessing the effectiveness of the application of a particular technology is capital costs and the payback period.

Within the framework of the study, the assessment of the power unit under consideration cost was made on the basis of recommendations for assessing specific capital costs and their distribution over equipment. [12]

It is proposed to evaluate the efficiency of commissioning a new power unit using net present value (NPV) [13]:

\[
NPV = \sum_{t=0}^{N} \frac{CF^t}{(1 + i)^t} - IC
\]

where:
\( t \) – the period of time for which it is necessary to calculate the net present value;
\( N \) – the number of periods (months, quarters, years) for which the estimated project needs to be calculated;
\( CF' \) – expected cash flow (net) for a specified time period;
\( i \) – the estimated discount rate for the estimated investment option;
\( IC \) – the amount of initial investment.

3. Results

According to proposed methodology calculations were performed to analyze the technical and economic efficiency of dual-fuel CCPP with a parallel operation scheme. Two options for applying the technology under consideration were considered: for subcritical initial steam parameters \((p_0 = 13 \text{ MPa}, t_0 = 540 \degree \text{C})\) and for supercritical \((p_0 = 24 \text{ MPa}, t_0 = 545 \degree \text{C})\).

Based on the calculation results given in table 1 it can be seen that an increase of steam’s initial parameters makes it possible to increase the efficiency of electric power generation by an average of 2\%. In passing from autonomy mode to a CCPP mode the efficiency increases by 22\%.

| Table 1. Technical and economic indicators of the installation. |
|---|---|---|---|
| Quantity | UM | 13 MPa, 540 °C | 24 MPa, 545 °C |
| Heat flow supplied to the gas turbine | MW | 211.34 | 211.34 |
| Steam flow condition per turbine | Kg/s | 163.92 | 163.92 |
| Heat supplied during the operation of a STU as part of a CCPP | MW | 362.18 | 351.99 |
| STU net efficiency in autonomy mode | % | 39.68 | 40.59 |
| CCPP net efficiency | % | 48.65 | 49.53 |

In addition, it should be noted that the equivalent fuel consumption has decreased (Figure 3). With an increase of steam’s initial parameters, the equivalent fuel consumption is reduced by an average of 3\%, and the operation of the STU as part of the CCPP makes it possible to reduce the equivalent fuel consumption by 21\%.

![Figure 3. Equivalent fuel consumption’s changing.](image-url)
Table 2 shows the results of calculating capital investments and costs in the construction of a power unit "from scratch". As is seen from the results, with an increasing of initial steam parameters, the total capital costs increase. This is primarily due to the capital costs increasing for the steam boiler: since an increasing of initial parameters leads to steel intensity increasing and more heat-proof steels using.

A graphical interpretation of the calculating results of the net discounted income for unit operating on the subcritical and supercritical parameters are shown at Figure 4 respectively.

| Quantity                  | UM       | 13 MPa, 540 °C | 24 MPa, 545 °C |
|---------------------------|----------|---------------|---------------|
| Steam boiler              | RUB million | 7 124.05    | 8 824.68    |
| Steam turbine             | RUB million | 2 966.04    | 2 892.96    |
| Gas turbine               | RUB million | 2 955.57    | 2 955.57    |
| Waste heat boiler         | RUB million | 202.00      | 202.00      |
| Electrical part           | RUB million | 2 046.24    | 1 980.72    |
| APCS                      | RUB million | 1 713.60    | 1 668.24    |
| Steam-water tract         | RUB million | 3 356.64    | 3 984.12    |
| Installation and commissioning | RUB million | 1 837.08    | 1 779.12    |
| Construction works        | RUB million | 4 427.64    | 4 205.88    |
| Project cost              | RUB million | 1 333.08    | 1 401.12    |
| Total capital investments | RUB million | 27 961.94   | 29 894.41   |

| Costs                     | UM       | 13 MPa, 540 °C | 24 MPa, 545 °C |
|---------------------------|----------|---------------|---------------|
| Fuel costs                | RUB million | 1 188.75    | 1 174.65    |
| Fixed costs               | RUB million | 3 705.02    | 3 960.10    |
| Total costs               | RUB million | 4 893.77    | 5 134.76    |
| Cost of electricity       | RUB       | 2.67         | 2.80         |

**Figure 4.** NPV for CCPP
4. Conclusion
Thus, the results of the calculations shows that using of a dual-fuel CCPP with a parallel operation scheme makes it possible to increase the efficiency of electric power generation by an average of 22% compared to operation in the coal-fired STU mode. In addition, the transition to the CCPP mode allows reducing the equivalent fuel consumption by 21%. The achievement of such results is primarily due to the division of the feed water flow into two parallel flows by integrating a gas turbine. [14] It is also should be noted the improvement of the power unit’s efficiency indicators in passing to supercritical steam parameters by an average of 2%. It is worth noting that the increasing of the electric power generation efficiency obtained in this work is confirmed by studies performed earlier [15]. Capital costs for the construction of the considered power unit "from scratch" amount to 29 billion rubles with a discounted payback period – 13 years from the beginning of construction.

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