Exergy analysis of dual-fuel combined cycle plants

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Abstract. An alternative to coal technology in regions with a significant share of gas in the fuel balance can be the transition to dual-fuel combined cycle gas turbine plants. The article considers five technological profiles of cogeneration combined cycle gas turbine power unit: with a low-pressure steam generator; with coal gasification; with gas line heater; with gas line heater and freon thermotransformer; dump type with a binary coefficient equal to one. A comprehensive analysis of cogeneration plants was carried out. The perfection of the thermal design of a combined cycle gas turbine power unit of each type is evaluated by the exergy structural coefficient. An analysis the criterion of technical and economic efficiency, exergy efficiency for the supply of electricity and thermal power for combined cycle power plants in comparison with traditional cogeneration power units in the power range of 50 ... 250 MW are also given.

1. Introduction
In the context of changing the structure of the fuel balance of the regions of the Russian Federation and the actual dual-fuel option, the issue of increasing the efficiency of generating electric energy is relevant. An alternative to “pure” coal technology in regions with a significant share of gas in the fuel balance can be the transition to dual-fuel combined cycle plants (CCGT) (figure 1, 2). Such installations can find application not only in the construction of new energy facilities, but also in the reconstruction of existing ones.

![Diagram of CCGT](https://example.com/diagram.png)

(a) With low pressure steam generator  
(b) With integrated gasification

**Figure 1.** Technological profile of CCGT:
1 - steam generator; 2 - steam turbine; 3 - electric generator; 4 - coal supply; 5 - gas turbine engine; 5a - gasifier; 6 - gas supply; 7 - installation for the separation of CO-hydrogen mixture; 8 - hydrogen consumer.
The selection of the most favorable parameters and dual-fuel CCGT schemes is determined, on the one hand, by the prospects and high efficiency of the technology, and, on the other hand, by the variety of possible combinations of commercially available units and installations, and the possibilities of designing new equipment. Technical solutions are possible, including as part of the modernization of existing plants without restrictions on the use of primary fuel.

2. Exergy analysis: structural coefficient
A comprehensive analysis of cogeneration CCGT units was carried out for five technological profiles: with a low-pressure steam generator (CCGT-LPSG); with coal gasification (CCGT-GF); with gas line heater (CCGT-GLH); with gas line heater and freon thermotransformer (CCGT-GLH FTT); dump type with a binary coefficient equal to one (BCCGT) [1–4].

For exergy analysis, the technological scheme of TPP power units is divided into subsystems (elementary functioning parts) connected by overflow of material exergy carriers (fuel, air, combustion products, steam, water, electricity, mechanical transmission, etc.) (figure 3) [5–7].

![Diagram of the functioning parts of the power unit connection](image)

**Figure 3.** The diagram of the functioning parts of the power unit connection: $E^x$ – incoming exergy stream of the corresponding functioning part; $E^y$ – exergy discharge stream of the corresponding functioning part; $X$ is the set of indicators characteristic of the corresponding functioning part (used as a set of solutions for thermodynamic, consumed, structural and circuit parameters and indicators); $Z$ – describes expenses involved in the creation and operation of the corresponding part of the power unit; $\lambda$ is the cross section.
The perfection of the thermal design of a CCGT unit of each type is evaluated by the exergy structural coefficient $(f)$ (Figure 3), taking into account the interconnections between the functioning parts of the power unit, as well as external system connections:

$$
\varepsilon_S = \left( \frac{\eta_{E_1}}{E_1} \right)^{-1} \left[ 1 - \eta^{-1} \prod \left( \frac{\eta_j}{E_j} \right) \right],
$$

where $\eta_i$, $E_i$ – exergy efficiency, inlet and outlet exergy stream of the first part (steam generator with all auxiliary systems) $\eta_j$, $\eta_j$ exergy efficiency of the $i$-th and $j$-th functioning parts, respectively.

The higher structural coefficient, the closer the circuit is to the serial structure and equal to unity, in case of feedback absence in the power unit circuit. This indicator affects the efficiency of production output /supply – the higher the indicator, the higher the efficiency is. All considered technologies have benefits in comparison with a traditional power unit. The exception is CCGT with low-pressure steam generator; on T-180 and T-250 turbines. This is due to the low binary coefficient for these options. The binary coefficient was not determined in this section, however, the relative power generation by the gas-turbine part of the installation (which indirectly characterizes it) is below 36%, and the relative increase in the structural coefficient is observed only from 40%, which characterizes all the other options considered.

3. Exergy efficiency of various CCGT technological schemes

Putting gasifiers into the CCGT-LPSG translates them into the CCGT-GF version and improves the structural perfection of the power unit (Figure 4). On the one hand, this is due to the displacement of the regeneration system in the steam turbine part (a decrease in the effect of exergy feedback on the steam-gas generating part of the CCGT unit), and on the other hand, the introduction of a gas tank to reserve syngas during partial failures.

![Figure 4. Relative exergy structural coefficient: $\varepsilon_S, \varepsilon_S^w$ – the exergy structural coefficient of CCGT and for conventional pulverized coal steam turbine power units, respectively; $N_{STU}$ – capacity of steam turbine power unit (STU).](image)

The structural efficiency of the BCCGT unit is higher than for the traditional power unit, since, due to the practically truncated regeneration system, the binary CCGT profile is closer to the serial structure.

For CCGT-GLH and CCGT-GLH FT, the structural coefficient increases by 4 ... 12% compared with traditional power units.

The output efficiency of each type of product is determined considering the systemic effect due to the entry of the investigated power unit into the electric and heat networks, ensuring the necessary reliability of energy supply and the impact on the ecological infrastructure. The systems of the functioning parts of the investigated power units have a series-parallel structure, in which feedbacks are implemented in accordance with the technological scheme.
Effectiveness evaluation of various CCGT technological schemes for the supply of electricity and thermal power shows that CCGT allows to obtain exergy efficiency for the supply of electricity in 1.1 ... 1.5, and for the release of thermal power – in 1.05 ... 1.2 times in comparison with traditional heating power units (figure 5, 6).

![Figure 5](image1.png)  
**Figure 5.** Relative exergy efficiency for power supply of CCGT ($\eta_N$) and traditional steam-turbine power unit ($\eta_{NT}$): the designations are the same as in figure 4.  

![Figure 6](image2.png)  
**Figure 6.** Relative exergy efficiency for tempering of combined CCGT ($\eta_T$), and traditional steam-turbine power unit ($\eta_{NT}$): the designations are the same as in figure 4.

An exergy assessment of the effectiveness of CCGT-GF the supply of synthesis gas to external consumers was not taken into account. The efficiency for the release of synthesis gas for such an installation based on the T-180 turbine is about 0.43.

Obviously, BCCGT have the best efficiency indicators, since they have the highest thermodynamic efficiency of processes and lower energy costs for their own needs. At the same time, the technological profile of a single-shaft BCCGT is formed using steam turbines with a unit capacity of about 100 MW or less. The use of larger steam turbines forms a two-shaft BPGU technological profile with at least two powerful gas turbines, which complicates the design and technological scheme of the power unit.

Figure 7 shows the criterion of technical and economic efficiency $\eta_Z$ for combined cycle power plants in comparison with traditional cogeneration power units in the power range of 50 ... 250 MW. This criterion, in essence, is a certain indicator of the profitability of technologies, since it takes into account the integral effect on the sale of products and the costs associated with its production.

![Figure 7](image3.png)  
**Figure 7.** Relative indicator of technical and economic efficiency: $\eta_Z$ – indicator of technical and economic efficiency for CCGT, $\eta_{Zf}$ – for pulverized coal-fired traditional cogeneration steam turbine power units.
From the above data it can be seen that CCGT-LPSG, CCGT-GF are 1.1 ... 1.5 times more efficient than traditional power units, and BCCGT – 1.6. This is due not only to the exergy efficiency of the CCGT, but also to lower costs caused by systemic influencing factors, as well as the stability of circuit-parametric decisions in the face of changing systemic factors (price, infrastructural, environmental).

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