Optimization studies of coal-fired combined cycle power plant given fuel price uncertainty

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Abstract. Integrated gasification combined-cycle plants are considered as one of the promising directions for the development of thermal power plants using fossil fuel. Interest in this area is explained by large natural reserves of coal and minimal harmful emissions into the atmosphere during the process of generator gas combustion. The aim of the study is to make the relationship between the specific investment and the efficiency of integrated gasification combined-cycle plant and to perform the optimization researches according to the criterions of minimum electricity price.

1. Introduction
Integrated coal gasification combined cycle power plants (IGCCPP) are promising plants with high energy, economic and environmental efficiency. The IGCCPP are complex power plants, consisting of a large number of different types of technologically connected components. Therefore, the choice of their parameters is a difficult task, which can be properly accomplished only by using mathematical modeling methods. The studies on IGCCPP were the focus of many papers [1,4,5], however, they did not perform co-optimization of cycle parameters and design parameters of the flowchart components. At the same time, the coordinated choice of a large number of parameters can be made only by the methods of mathematical modeling and optimization.

The Melentiev Energy Systems Institute has developed the methods to automate the mathematical modeling of complex thermal power plants, optimize their flowcharts and parameters. Researchers of the Institute have constructed mathematical models for the components and flowcharts of the power plants of different types, and conducted optimization studies of a number of power plants of different power levels [3]. As evidenced by the studies of coal-fired steam turbine plant (STP), the relationship between the specific investment (SI) and the efficiency has a point of minimum. Therefore, it is advisable to conduct the studies in the interval between this point and the point with the maximum efficiency.

This paper, sets the objective to verify, on the basis of the optimization studies, whether the IGCCPP has the same properties as the coal-fired STP and to determine the dependence of the optimal techno-economic indices and the main parameters of the plant on the coal price.

2. Description of integrated gasification combined-cycle power plant
The plant at issue (Figure 1) consists of 3 blocks: gasification, gas turbine and steam turbine. The main components of the gasification block are: a fuel preparation subsystem, a gasifier proper that consists of
a reaction chamber in which coals is gasified and a cooling system where the gasification products are cooled and transfer their heat to water or steam.

![Diagram](image)

**Figure 1.** A calculated scheme integrated coal gasification combined cycle power plants.

The gas turbine block includes: an air compressor, a combustion chamber and a gas turbine (GT) located on the same shaft as the compressor. The main components of the steam turbine block are: a waste heat boiler where the exhaust gases from gas turbine are supplied (steam superheater, evaporator and economizer surfaces are located in the waste heat boiler), a steam turbine (ST) and a condenser.

We developed a mathematical model of an IGCCPP, based on the developed mathematical models of its components with the help of the software “Computer-based system for program building” (CSPB) [3]. This software makes it possible to build a model of the power plant as a whole based on the given mathematical models of the components and technological links between them. In this study, we used the mathematical models of a gasifier, and combustion chambers of gas turbines, that are based on the energy and material balances; the models of gas-water and gas-vapor radiation and convective heat exchangers that are based on the normative methods of thermal, aerodynamic and hydraulic calculations of boiler units. These models were developed at the Melentiev Energy Systems Institute SB RAS.

The CSPB software was also used to develop a mathematical model of an integrated gasification combined-cycle plant. The model includes 693 initial parameters, 11 iterative-refined parameters and 745 calculated parameters.

3. Technical and economic studies of the integrated gasification combined-cycle power plant

The optimization studies involved a methodological approach developed at the Melentiev Energy Systems Institute SB RAS to compare the efficiency of complex thermal power plants [3]. The approach is aimed at determining the relationship between the net efficiency of the power plant and the minimum (at this efficiency) specific investment, and includes the following steps.

- Solve the problem of optimizing the power plant parameters by the criterion of the maximum net efficiency, given physical and technical constraints on the parameters (as a result, the maximum possible energy efficiency of the plant is determined).
- Solve the problem of finding the minimum specific investment in the plant (as a result, the net efficiency is determined at which the specific investment reaches a minimum).
- Assume a range of variation in the net efficiency, within which it is expedient to conduct a study of the economic efficiency of the plant. The upper limit of this range is the marginal efficiency, and the lower limit is the efficiency at which the specific investments reach a minimum. Within the assumed range of variation, the net efficiency is assigned several points equidistant from each other, that form a certain set of the efficiency values.
- Solve the problem of optimizing the power plant parameters according to the criterion of the minimum specific capital investment for each value belonging to the specified set.

Solving this set of problems allows us to obtain the relationship between the minimum possible investments in the power plant and its energy efficiency (net efficiency) at deterministic prices for certain types of equipment within the assumed range of the efficiency variation.

The optimization studies relied on the effective approach developed at the Melentiev Energy Systems Institute SB RAS based on the fact that the exact solution to the system of equations describing the IGCCPP, is reached at the optimal point [6]. This approach makes it possible to determine the range of rational values of the plant parameters and its techno-economic indices.

Seventy-one parameters were optimized for the IGCCPP. At the same time, 102 inequality constraints that form the region where the operation of the plant components is physically and technically feasible were taken into account.

The investment in IGCCPP was determined according to the methodology presented in [3]. The plant costs included the costs depending on the electric power, the costs depending on the amount of heat carried away from the steam turbine condensers, the costs depending on the price of the main heat-power equipment, the construction costs, and the costs depending on the amount of fuel consumed. The cost of the gasifier was assumed in proportion to the fuel consumption, the cost of turbomachines and pumps was assumed in proportion to their capacity, and the cost of heat exchangers was proportional to their mass or area of the heat transfer surface.

The following initial cost characteristics of the equipment components were assumed for the calculations: the constant component of capital investments is 8000 thousand USD, the specific cost of the gasification block is 4000 thousand USD/(kgce/sec), the specific cost of metal of the heat exchanger tubes made of ferritic steel – 100 USD/m², carbon steel – 80 USD/m², austenitic steel – 120 USD/m², specific cost of air compressors – 54 USD/kW, gas turbine – 72 USD/kW, steam turbine – 60 USD/kW. The number of the IGCCPP utilization hours was assumed to be 7000 hours.

The temperature of gases at the gas turbine inlet for all options was assumed to be the same and equal to 1427 °C.

The calculations were carried out for the coal of the Berezovskoye deposit [2].

Based on the calculations, we obtained a relationship between the specific investment in the IGCCPP and the efficiency (Figure 2).

![Figure 2. The dependence of the specific investment in the IGCCPP and the efficiency.](image-url)
In the same way, we carried out optimization calculations for the criterion of the minimum electricity price at a given internal rate of return (in the calculations it was assumed to be 0.15). The results of these calculations, as well as the calculation results for the criteria of the minimum specific investment and the maximum efficiency, are given in Table 1.

### Table 1. Result of calculation.

|                                | Min SI | Min electricity price |                          | Max efficiency |
|--------------------------------|--------|-----------------------|--------------------------|---------------|
|                                |        |                       | 50 USD/tce | 100 USD/tce | 150 USD/tce | 200 USD/tce |                  |
| Gas temperature at gasgenerator outlet, °C | 800     | 800                   | 800         | 800         | 800         | 800         | 800               |
| Lower calorific value, MJ/m³ | 5.2     | 5.2                   | 5.3         | 5.4         | 5.4         | 6           |
| Gas pressure at gas turbine inlet, MPa | 0.96 | 1                      | 1.1         | 1.2         | 1.2         | 1.9         |
| Gas temperature at gas turbine outlet, °C | 870     | 851                   | 834         | 818         | 806         | 707         |
| Live steam pressure, MPa       | 15.3    | 15.2                  | 15.1        | 15          | 14.9        | 14.8        |
| Live steam temperature, °C     | 519.2   | 518.6                 | 518.2       | 519.9       | 519         | 526.1       |
| Live steam flow rate, kg/s     | 124.6   | 123.7                 | 122         | 121.3       | 119.8       | 101.8       |
| Reheat steam pressure, MPa     | 3.2     | 3.2                   | 3.2         | 3.2         | 3.2         | 3.4         |
| Reheat steam temperature, °C   | 480     | 480.9                 | 480.6       | 481         | 480.4       | 485.4       |
| Steam pressure in low-pressure evaporative circuit, MPa | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Steam flow rate of low-pressure evaporative circuit, kg/s | 6.7 | 6.8 | 6.8 | 6.6 | 6.7 | 5.4 |
| Net efficiency, %              | 45.2    | 46.6                  | 47.4        | 48.3        | 48.8        | 54.3        |
| Specific investment, USD/kWh   | 2361    | 2372                  | 2379        | 2389        | 2404        | 3144        |
| Electricity price, cent/kWh    | –       | 10.2                  | 11.5        | 12.8        | 14.1        | –           |

### 4. Conclusions

- The studies indicate that for the IGCCPP the relationship between the specific investment and the efficiency has a minimum which is reached at the point with an efficiency of 45.2% and a specific investment of 2361 USD/kW.
- The optimal gas pressure before the gas turbine varies from 0.96 MPa (minimum specific investment) to 1.9 MPa (maximum efficiency).
- The efficiency of the power plant for optimal values for the criterion of the minimum electricity price varies from 46.6% (50 USD/tce) to 48.8% (200 USD/tce).
- The studies demonstrate that when developing the IGCCPP making the decisions that ensure the maximum energy efficiency leads to a significant increase in specific investment and a decrease in the cost-effectiveness of the plant.
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