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# An approach to optimization of the choice of boiler steel grades as to a mixed-integer programming problem

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ABSTRACT

One of the ways to enhance the energy efficiency of thermal power plants is to increase thermodynamic parameters of steam. A sufficient level of reliability and longevity can be provided by the application of advanced construction materials (in particular, high-alloy steel can be used to manufacture the most loaded heating surfaces of a boiler unit). A rational choice of technical and economic parameters of energy plants as the most complex technical systems should be made using the methods of mathematical modeling and optimization. The paper considers an original approach to an economically sound optimal choice of steel grade to manufacture heating surfaces for boiler units. A case study of optimization of the discrete-continuous parameters of an energy unit operating at ultra-supercritical steam parameters, in combination with construction of a variant selection tree is presented.



## 1. Introduction

Thermal power plants play an important role in the world energy. The efficiency of their operation largely depends on a correct selection of flow charts and parameters characterizing individual processes that run in different components. Moreover, it is necessary to take into account a great number of physical and technical constraints and consider a great number of schematic solutions. Their selection on the basis of comparison and analysis of variant calculations can appear insufficiently close to the optimal. Therefore, it is sensible to solve such problems by using the methods of mathematical modeling and optimization. A considerable amount of studies have been carried out in this area over a number of years.

For example, in Ref. [1] the authors consider an improvement in thermodynamic characteristics of a plant operating on supercritical steam parameters in terms of cost-effectiveness.

The authors of [2] focus on modeling a boiler-turbine unit of thermal power plant using the methods of fuzzy – neural networks.

In Ref. [3] the authors present a CGAM - problem as a test case to compare various methodologies for thermo-economic optimization. The authors demonstrate a traditional solution of the optimization problem.

The research in Ref. [4] deals with optimization of the commercial triple-pressure reheat steam-air cooled gas turbine combined cycles (Regular 107H and Regular M501H). It involved the methods of direct search and variable metric.

In Ref. [5] the authors present optimization of a design of heat recovery steam cycles for two coal to Fischer-Tropsch fuel plants. The research involves the simplex method, Lozza's prediction method and constrained particle swarm optimization.

In Ref. [6] the authors present a thermodynamic optimization of combined cycle gas turbine power plant. The reduced gradient method is used to solve the nonlinear mathematical programming problem. A set of optimal solutions is demonstrated for the considered plant.

The authors of [7] consider energy, environmental and economic effectiveness as criteria for multi-objective optimization in the design of thermal systems. The plant from the CGAM-problem is presented as an example. The Pareto-optimal set of solutions obtained using an evolution algorithm is shown.

The authors of [8] apply simplex search and differential evolution based inverse methods to estimate some indices of steam turbine plant.

In the research from Ref. [9] the authors demonstrate the use of an evolution algorithm and fuzzy logic to optimize the stage of a combined cycle plant startup.

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**Nomenclature**

| | |
|---|---|
| AC | Air compressor |
| EBF | Energy boiler furnace |
| CPS | Convective primary superheater |
| CTS | Convective tertiary superheater |
| CSS | Convective secondary superheater |
| ISS | Intermediate secondary superheater |
| ZMHC | Zone of maximum heat capacity |
| IPS | Intermediate primary superheater |
| SE | Secondary economizer |
| AH2 | Secondary tubular air heater |
| PE | Primary economizer |
| AH1 | Primary tubular air heater |
| HPST | High pressure section of steam turbine |
| MPST | Medium pressure section of steam turbine |
| LPST | Low pressure section of steam turbine |
| CP1 | Circulation pump |
| CON | Condenser |
| CP2 | Condensate pump |
| LP1 | Low pressure heater 1 |
| LP2 | Low pressure heater 2 |
| LP3 | Low pressure heater 3 |
| LP4 | Low pressure heater 4 |
| DP | Drain pump |
| DEA | Deaerator |
| FWP | Turbine-driven feedwater pump |
| FWPT | Feedwater pump turbine |
| VC | Vapor cooler |
| HP1 | High pressure heater 1 |
| HP2 | High pressure heater 2 |
| HP3 | High pressure heater 3 |
| S | heating surface cost |
| IRR | internal rate of return |
| M | the number of steel grades |
| $N_i$ | the number of elements in the set $\Omega_i$ |
| I | the number of heating surfaces |
| $T_i^{act}$ | actual temperature value of the considered steel |
| $T_{con\ i}^{max}$ | the maximum temperature of the considered steel |
| $m_{sf_i}$ | specific heating surface cost |

*Greek symbols*

| | |
|---|---|
| $\Omega_i$ | a set of numbers of grades of materials from which the surface can be made |
| $\sigma_i^{act}$ | actual value of mechanical stress of tube material |
| ε | coefficient |

*Subscripts*

| | |
|---|---|
| sf | surface |
| j | an ordinal number of steel in the list of grades considered for the *i*-th surface |
| con | considered |
| act | actual |
| i | heating surface number |

*Superscripts*

| | |
|---|---|
| max | maximum |

The thermo-environmental and exergy-economic analyses are used to investigate the operation of a combined-cycle plant in Ref. [10]. The influence of operating parameters on such factors as the useful output power, energy efficiency, exergy efficiency and CO2 emissions is estimated. Optimal parameters are determined using the Nelder-Mead method.

The paper [11] presents a superstructure-free optimization approach to the synthesis and design of thermal power plants. The approach includes the evolutionary and deterministic optimization. A simple thermal power plant is considered as a case study.

The authors of [12] conduct a multi-objective optimization of the Brayton cycle facility. The optimization is made using an evolutionary algorithm and decision-making methods. The Pareto-optimal sets are obtained using non-dominated sorting genetic algorithm and multi-objective evolutionary algorithm based on decomposition.

The paper [13] is concerned with the optimization of a combined cycle biomass plant on the basis of genetic algorithm. Two design optimization cases are considered: with immersed particle heat exchanger and nickel alloy heat exchanger. An analysis of the relationship between the maximum thermal efficiency and electrical efficiency is presented.

The paper [14] presents the ANN-GA-based optimization of high ash coal-fired supercritical power plant.

As is seen from the presented studies, most of them apply various direct search methods that are characterized by simplicity and resistance to calculation errors. However, they allow us to optimize a small number of parameters, whereas to obtain a more complete idea on the operation of a plant we should optimize a much larger amount of parameters.

The researchers at Melentiev Energy Systems Institute have been developing gradient methods for optimization of energy plants and other complex technical systems over a long time [15,16]. A method "with memory" has been developed on the basis of a combination of known methods of "immersion" and "feasible directions" and proved high effectiveness when applied. The software "System of Computer—based Construction of Programs" was developed to generate a mathematical model of the plant in the form of a program for calculation in the high- level language on the basis of data about models of individual components and technological relations among them, form and solve optimization problems [17]. The optimization allows for equality constraints on optimized parameters, i.e. equations of energy and mass balances as well as other relationships describing operation of the plant, and inequality constraints that form a region where operation of the plant components is physically and technically feasible. Using this software we carried out technical and economic studies of various energy plant types [18–20] and obtained a number of design and parameter solutions.

## 2. Methodology of research

It should be noted that along with the optimization of such continuously varying parameters as gas pressure and temperature before gas turbine, pressure and temperature of live steam and reheat steam of a steam turbine plant, diameters of tubes and spacing between them for heat exchange surfaces of steam boilers and waste-heat recovery boilers of combined cycle plants, some discretely varying parameters should also be optimized. This concerns the quantity of paralleled components, for example, heat exchangers, pipelines of standard diameters, etc. This class of mixed optimization problems (with discretely and continuously varying