Development of a simulation model to research environmental index of a GTP-110 gas turbine operating as part of a combined cycle gas turbine power unit under changing operational and external climatic factors

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Abstract. Combined-cycle technologies to produce electrical and thermal energy are the most popular and promising all over the world. Their efficient application, however, has encountered a number of interdisciplinary problems. The present study was carried out on a mathematical model of a CCGT power unit. The results of the study are presented, allowing us to assess the impact of operational and environmental parameters on the stability of the combustion process in the combustion chamber of a GTP-110 gas turbine unit, and to determine the compatibility of environmental indicators with the standards for gas turbine operation with a wide range of loads, taking into account the technological and design constraints of thermal mechanical equipment. The main implementation features of a simulation model of a gas turbine unit (GTU) in the SimInTech dynamic modeling environment are considered.

1. Introduction
Combined-cycle technologies are a promising research area in the energy sector all over the world. At the same time, the development of innovative combined-cycle technologies revealed interdisciplinary problems. Firstly, changes in the operating efficiency of the gas turbine equipment depending on ambient conditions, that is, the actual location of the station. Secondly, the features of the technological process associated with the limitation of several operating parameters of the installations due to significantly different dynamic properties of jointly operating equipment (steam and gas turbines) [1–4].

During the operation of a gas turbine unit, the important control parameters are electrical power, environmental emissions, rotor speed, etc. The issues of reducing the concentration of harmful emissions (CO₂ and NOₓ), which depend on the presence of high-temperature combustion zones inside the combustion chambers (CC) of gas turbine engines, are especially urgent. It should be noted that the gas turbine compressor station provides a high level of fuel combustion efficiency with high efficiency; therefore, the content of unburned carbons, including methane, is insignificant and within the permissible values. The most likely reasons for the emission of carbon oxides (CO) are the following: insufficient oxygen in the CC; chemical reaction disorder; brief presence of the reacting mixture in the combustion zone.
In general, modern gas turbines (GT) operating on natural gas show extremely low nitrogen oxide emissions. However, the limit standards regarding harmful gaseous emissions during the operation of GTP and combined cycle power units (CCGT) are periodically toughened. This is apparently due to modernization of GT and operation of more advanced (promising) low-emission combustion chambers (LECC). Under loads close to nominal, the introduction of low-emission combustion technologies makes it possible to obtain concentrations of $\text{NO}_x = 10 \ldots 20 \text{ mg/m}^3$ and $\text{CO} = 30 \ldots 150 \text{ mg/m}^3$ in GTP emissions by supplying a mixed fuel-air mixture to the combustion chamber in two or more flows at different cross sections. At the same time, this fuel combustion technology requires the provision of (provide) special means for regulating the composition of the fuel-air mixture to maintain emission characteristics within the range of the required operating conditions of the gas turbine plant [5-9].

The requirements regarding nitrogen oxides concentrations are established by Russian national standards, according to which the permissible level of $\text{NO}_x$ should not exceed 150 mg/m$^3$. The requirements $\text{NO}_x \leq 100 \text{ mg/m}^3$ are applied for modern low-toxic CC, and $\leq 50 \text{ mg/m}^3$ for low-emission CC.

It should be noted that in accordance with the Russian import-substituting program regarding power generation capacity, attempts are being made to launch production of medium and high power gas turbines (GTP-65, GTP-110 and GTP-170) [3; 10]. At the same time, Siemens, company in the production of gas turbines, claims $\text{NO}_x$ emission values of up to about 48 mg/m$^3$ for a turbine of similar power SGT-2000E (117 MW).

Let us consider the results of the study, which allow us to assess the impact of operation parameters and environmental index on the stability of the combustion process in the combustion chamber of a gas turbine unit as part of a CCGT unit and to determine the compatibility of environmental indicators with the standards. Since emission parameters are checked by environmental authorities, penalties are established if these parameters are exceeded. There is thus a need to minimize and maintain emissions within acceptable limits by improving control systems.

2. Materials and methods

2.1. Features of mathematical modeling of a technological facility

In general, simulation and mathematical modeling make it possible to increase the efficiency of research at the early stages of gas turbine design and purchase of equipment. Modeling makes it possible to speed up the development of high-precision control systems and to use models of power units with a CCGT to assess the efficiency of process equipment (for example, a gas turbine compressor) under various environmental conditions. The structural and basic design technical characteristics of process equipment and the results of thermal-hydraulic calculations are used as the initial data in the modeling. The mathematical model of the GTU is considered as a single power engine, consisting of a compressor, a combustion chamber with combustion and cooling zones, and a gas turbine. The main disadvantage of modeling is the lack of information about the course of processes in complex thermal mechanical equipment, for example, a gas turbine combustion chamber. This disadvantage necessitates simplification of thermophysical processes, which reduces the value of model results.

The mathematical model [2; 3] is based on the laws of conservation of nonequilibrium thermodynamics. The use of a fundamental physical and mathematical basis makes it possible to strictly assess the impact of the accepted assumptions, external and mode factors on the quality of the result.

The mathematical model describes the operation of the following interconnected equipment of the CCGT unit. The initial data for the development of a mathematical model to calculate emissions in gas turbines are the following: number of gas turbines connected to the chimney; chimney parameters; fuel composition and consumption; technological dimensions of the combustion chamber, etc.

The mathematical model [2; 3] is supplemented with the following equations: oxygen concentration in the combustion zone; average thermal stress in the CC; concentration of thermal and fast nitrogen oxides for natural gas; mass flow rate of nitrogen oxide emissions, etc.
2.2 Feature of simulation of a technological facility

Based on the developed mathematical model of a gas turbine and CCGT power unit, a simulation model was developed in the SimInTech software package [11]. A simulation model (polymodel complex) of power units CCGT-325, CCGT-450 and CCGT-800 [2; 3] was used to carry out the research.

The peculiarities of implementing the mathematical model of the CCGT unit in the SimInTech software package are [2; 11]: in the structural design of logical-dynamic systems described in input-output relations, together with systems of ordinary differential equations; an open interface for developing your own libraries, as well as the ability to connect third-party software modules in various programming languages.

The requirements for an acceptable degree of model complexity should be considered. Since the model of a power unit with a CCGT unit is to be integrated into the real-time environment of the software and hardware complex (SHC) of the process control system, the number of heating surface subdivisions in a waste heat boiler, for example, is determined by the minimum number of necessary requirements for valid modeling of thermodynamic processes using the available tools.

It has been experimentally established that for a correct calculation in the model, it is necessary to use the second order Runge-Kutta numerical integration method for solving systems of differential equations. Other the methods do not ensure solution of the differential equations system of the developed mathematical model of a power unit with CCGT. The one-step explicit 4th and 5th orders Runge-Kutta methods have shown the same calculation accuracy during operation of the developed model as the 2nd order Runge-Kutta method, but the calculation speed has turned out to be much lower.

3. Verification of the obtained model results

Verification of the obtained results has been carried out by comparing simulation results with operating condition trends (data are from the archive of the automated process control system of the CCGT-325 power unit of Ivanovskie CCGT). Figure 1 shows the comparison results of the model. The authors have also presented the results of modeling the calculation of emissions in exhaust gases, namely, the mass flow rate of NO$_2$ and the concentration of nitrogen oxides NO$_x$ at the GT outlet.

![Figure 1](image)

*Figure 1. Technological parameters change: 1 – model; 2 – trend from the control system archive; \(N_{\text{gt}}\) – electric power of GT; \(T_{\text{gt}}\) – temperature of GT exhaust gases; t – time.*

The results of the study show that the developed simulation model operates properly with minor static deviations, related to the assumptions made during the development of the mathematical model.

4. Assessment the impact of operating factors on the concentration of NO$_x$ emissions

Let us consider the influence of GT emissions using the example of a CCGT-325 power unit. A number of simulation model experiments have been carried out, and the performance indicators of the GT in the steady state (statics) have been recorded with variations in a number of input parameters:
ambient air temperature, fuel consumption, opening angle of the compressor inlet guide vane (IGV), ratio of air consumption for cooling the GT blades.

Figure 2 shows that regardless of the thermal mode, the concentration of nitrogen oxides in the exhaust gases from the gas turbine (solid line) during combustion of the same amount of natural gas increases when the compressor IGV is closed. In addition, closure of the IGV also influences the temperature of the exhaust gases from the gas turbine (dashed line), which results in deterioration of combustion processes and an increase in thermal nitrogen oxides, which in turn increase the total number of nitrogen oxides. According to the requirements of the performance chart, the temperature at the gas turbine outlet should not exceed 517 °C for normal operation of the waste heat boiler. At the same time, a safe value of the temperature at the GT outlet in the range of ambient air temperature variations -20 ... 30 °C is possible only for a fully open IGV compressor (a design feature of the unit).

![Figure 2](image)

Figure 2. Impact of the opening angle of the compressor IGV (a) and influence of fuel consumption (b) on the value of nitrogen oxides concentration in gas turbine exhaust gases at varying ambient air temperature: 1 – minus 20 °C; 2 – plus 15 °C; 3 – plus 30 °C; $C_{NOx}$ – concentration of nitrogen oxides in GT exhaust gases; $T_{gt}$ – temperature of GT exhaust gases; $B$ – fuel consumption.

Also, figure 2 shows that the temperature at the combustion chamber outlet (dashed line) increases with increased supply of natural gas to the combustion chamber, leading to growth of thermal nitrogen oxides in the composition of the exhaust gases. The graph shows that a decrease in emissions becomes possible with a decrease in fuel consumption, but this leads to a significant decrease in gas temperature at the gas turbine outlet, which is ineffective for normal operation of the waste heat boiler (the efficiency of the CCGT unit as a whole decreases).

Figure 3 shows that a decrease in the concentration of nitrogen oxides is observed (solid line) with an increase in the proportion of cooling air. It should be noted that a change in the air ratio from 14% and above does not significantly affect the decrease in the concentration of nitrogen oxides. Therefore, the nominal value of air bleed for GT cooling in the region of 13 ... 14% for the design mode of the GTU, as confirmed by the studies, is justified.

![Figure 3](image)

Figure 3. Effect of changing the ratio of air flow rate for cooling of GT vanes on the value of nitrogen oxides concentration in gas turbine exhaust gases at varying ambient air temperature: 1 – minus 20 °C; 2 – plus 15 °C; 3 – plus 30 °C; $G_{ca}$ – proportion of cooling air.

The impact of changes in GT load on its environmental performance during operation as part of a CCGT power unit was held. Values are considered at an ambient air temperature ($T_{o.a.}$) of 15 °C (nominal mode) and -20 °C (average ambient air temperature in winter in Ivanovo Region). The load
change was carried out in accordance with the performance chart in the range of 60 ... 110 MW, while the gas turbine outlet temperature was maintained at a safe level of 517 ºС (due to the ratio of fuel consumption values and IGV opening angle). Such a temperature is necessary for safe operation of the GT. Since the composition of the fuel entering the gas turbine combustion chamber is assumed to be unchanged in the model, the total volume and enthalpy of combustion products at the gas turbine outlet remain constant in all operating modes and amount to 16.1 m³/m³ and 38.7 MJ/m³, respectively. Some results of assessing the impact of the load on the environmental performance of GT at an outside air temperature of 15 degrees: concentration of thermal nitrogen oxides (3.22 mg/m³ for 60 MW and 3.88 mg/m³ for 110 MW); total concentration of thermal and fast nitrogen oxides (116 mg/m³ for 60 MW and 127 mg/m³ for 110 MW); mass flow rate of nitrogen oxides (27.2 g/s for 60 MW and 41 mg/m³ for 110 MW). According to national standard (GOST) requirements, NOₓ emissions should not exceed 150 mg/m³.

The simulation model operates as part of a polymodel complex of power units with a CCGT. This makes it possible to conduct studies to assess the effect of excess air on nitrogen oxide emissions, taking into account the technological areas of the GTP [3]. During the studies, ambient air temperature was changed within the range of -20 ... 30 ºС, with a load of 48 ... 110 MW. The highlighted area (figure 4) shows the design and operating limits of the operating range of the gas turbine load.

![Figure 4. Impact of excess air ratio on nitrogen oxide emissions in the technological (process) areas of the gas turbine unit at varying ambient air temperature.](image)

In figure 4 it is indicated: 1 – plus 30 ºС (N₉ = 98 MW); 2 – plus 15 ºС (N₉ = 110 MW); 3 – minus 20 ºС (N₉ = 85 MW); I – combustion zone in the combustion chamber; II – mixing (cooling) zone in the combustion chamber; III – zone of gas supply to GT; IV - zone of gas exit from GT; N₉ – electric power of GT; Cₙₒₓ – concentration of nitrogen oxides in GT exhaust gases; α – excess air ratio.

The graph shows that a decrease in emission concentration to the permissible value of 150 mg/m³ and below occurs at the border of the technological (process) area of supplying combustion products to the gas turbine (zone III); further, taking into account additional air flow from the compressor for cooling the turbine blades, the concentration of emissions declines.

5. Conclusion

Thus, according to the results of the study, the following conclusions can be drawn:

- A simulation model of a gas turbine has been developed. It includes a part for calculating the environmental performance of the GTP-110 turbine, which makes it possible to assess changes in the concentration of NOₓ emissions in a wide range of loads and changing environmental factors.
- The authors have obtained the dependences of NOₓ emissions on ambient air temperature during operation of the gas turbine unit in a wide range of loads, with safe flue gas temperature maintained at the GT outlet.
The results of studying the impact of operating factors on the concentration of NO\textsubscript{x} emissions out the GT have shown that when the turbine operates near an ambient air temperature of 30 °C, the design features (limitations) of the compressor are manifested. A safe value of flue gas temperature behind the GT is achieved only when the IGV is fully open. The obtained results have also shown that when the ratio of the air flow rate for cooling the GT blades changes with an air bleed fraction of 14% and higher, the concentration of nitrogen oxides in as turbine exhaust gases does not change significantly. The studies have been carried out by the methods of simulation, implementing the mathematical dependences of GT operation. Analysis of the obtained results shows the possibility of their efficient practical application in solving tasks related to improving automatic control systems for gas turbines.

In general, the conducted studies of the GT unit in the operating load range of 48 ... 110 MW with ambient air temperature variations in the range of -20 ... 30 °C show that emission standards requirements are fulfilled in the whole load range of the GTP. However, the concentration of emissions has a rather low possible deviations (10% or 15 mg/m\textsuperscript{3}), which is not significant regarding the possibility of stricter environmental safety requirements.

The resulting simulation model and test results allow us to study the possibility of introducing new technologies of fuel-air mixture combustion in high-temperature combustion chamber zones of modern gas turbines, and ensuring their environmental performance.

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