Stabilization of gas turbine unit power

I Dolotovskii¹ and E Larin¹

¹ Department of Thermal and Nuclear Power named after A Andryushchenko, Gagarin Saratov State Technical University, 77 Polytechnic street, Saratov 410054, RU

E-mail: dolotowsky@mail.ru, larin@sstu.ru

Abstract. We propose a new cycle air preparation unit which helps increasing energy power of gas turbine units (GTU) operating as a part of combined cycle gas turbine (CCGT) units of thermal power stations and energy and water supply systems of industrial enterprises as well as reducing power loss of gas turbine engines of process blowers resulting from variable ambient air temperatures. Installation of GTU power stabilizer at CCGT unit with electric and thermal power of 192 and 163 MW, respectively, has resulted in reduction of produced electrical energy production costs by 2.4% and thermal energy production costs by 1.6% while capital expenditures after installation of this equipment increased insignificantly.

1. Introduction

Gas turbine units (GTU) are widely used for modernization and renovation of thermal power plants and boilers equipment as well as for construction of new electric and thermal power sources based on cycle gas turbine sources (CCGT-TPS) of various output capacity [1–3]. In addition, gas turbine engines currently find widespread application as one of primary types of gas compressor units (GCU) for compressor stations and as engines for process blowers (PB) at petrochemical industrial facilities. At the same time, classic CCGT units are constructed by combining gas turbine and steam turbines cycles operating using their own cycle arrangements. A similar design is used for outfitting GTU of GCU and other PB with waste heat boilers (WHB) equipped with extended furnaces and air and fuel supply lines. This enables autonomous operation of all energy producing units during variable operation modes of GCU and PB.

Prevalence of CCGT units within the structure of power production facilities currently under construction can be explained by their high performance characteristics: their output reaches 58-60% [3, 4] (with predicted improvement to 65%); they have high mobility [5]; fast construction period (no more than two years from start to finish); and small payback period (no more than 4-6 years), thus making them very attractive for any potential investors. It should be noted that GTU output is not the only criterion for evaluating efficiency of gas turbine technologies for power production facilities. Generally, some kind of a resulting parameter, such as the cost of production of 1 kW·h of electric power during the whole unit operating period, serves as a viable criterion for evaluating its total efficiency. At the same time, one should also account for variable operation modes and corresponding decrease of power production characteristics of GTU (its available capacity and production output) at high ambient air temperatures (or some gas turbine units increment of ambient temperature from 15°C (nominal value) to 35°C can reduce effective power output by 25% [6]). If the ambient air temperature is lower than 4°C, the unit must implement a specific design in order to provide safe operation of GTU [3] without using costly air heater system for a combined air treatment unit.
The proposed novel unit [7] design allows increasing power capacity of GTU integrated into CCGT units and energy and water supply systems as well as stabilizing power output of gas turbine engines operating in variable conditions.

2. Structure and equipment composition of GTU power output stabilization system

GTU power output stabilization system includes three units (see figure): air preparation (cooling and drying) before it enter the GTU air compressor; water cooler installed in steam-jet refrigerating unit and energy and water supply system. The latter consists of steam boiler 15, which utilizes the heat of GTU exhaust air, condensing steam turbine 18 with power generator 19 and gas cooler 16, where water vapors are condensed from exhaust gases.

![Schematic scheme of CCGT with the installation of power stabilization GTU.](image)

**Figure.** Schematic scheme of CCGT with the installation of power stabilization GTU.

Units: GTU – gas turbine unit; APU – air preparation unit; WCU – water cooling unit; IEWS – installation of energy- and water supply; physical flows: A and AC – atmospheric and cooled air respectively; CWP – condensate of water vapour; WV – water vapour; WT – water technical; GD – gases of the degassing; GF – gas for the fuel; ED – effluents to drainage; EG1 and EG2 – exhaust gases; HD and CD – heated and cooled distillate respectively; DW and RW – direct and return water (respectively) of the heat supply system; OS – overheated steam; HHW – water for the installation of preparation house-hold water; apparatuses: 1 – combustor; 2 – air compressor; 3 – gas turbine; 4 and 19 – consumers of mechanical energy (electrical generating units); 5 – scrubber of air; 6 and 11 – filters; 7, 10, 14, 22 and 23 – pumps; 8 – evaporator; 9 – vacuum-compressor; 12 and 21 – air cooling apparatuses; 13 – tank of condensate; 15 – waste heat recovery boiler; 16 – gas cooler; 17 – chimney; 18 – steam turbine; 20 and 25 – heat exchangers - water heaters; 24 – steam jet pump; 26 – expander generator; 27 – electric gas heater

Stabilization of GTU power output and increased efficiency of electric and heat power generation in CCGT unit for system operating in different from nominal conditions can be achieved by using the following design and engineering solutions.

Installation of expander generation at the input flow of fuel gas, that also produces electric power used for heating said gas, provides a completely anhydrous operation mode for gas supply system which
helps to reduce fuel gas consumption for heating the flow of expanding gas compared to traditional engineering solutions.

Using cooled distillate to cool cycled air in its preparation unit helps to increase gross output of air compressor, thus, excluding the possibility of GTU power loss during hotter months. Meanwhile, induction of air flow with concurrent water jet streams (dispersed by nozzles) almost completely eliminates all aerodynamic losses of air washer and provides maximal power capacity among currently existing designs while dust removal from air prolongs service life of GTU due to decreased erosion and wear of turbine blades.

Installation of steam-jet refrigerating unit helps to maintain required air temperature (at nominal level) before GTU air compressor. Cooled distillate is produced by refrigerating unit as a result of heat loss by vaporization which is intensified by vacuum produced by vacuum compressor. Distillate from refrigerating unit vaporizer is transferred to nozzles of the second stage of air washer which helps to exclude the risk of ice formation within stream part of air compressor during colder months and prevent unit’s power output and service life decrease.

Two-stage cooling of exhaust air after WHB and subsequent condensation of water vapors is provided by two inducting streams – process water and cooled condensate. This helps to reduce gas dynamic losses within exhaust air duct of GTU. Providing unit connections for cooled and de-aerated water condensate helps to send it directly to nozzles of the first stage of air washer, use it for WHB and heat supply system as well as for potable water preparation unit.

3. Methodology of calculation of energy and economic parameters of the process

Heat engineering calculations for unit elements were performed using mathematical model consisting of a series of similar blocks corresponding to description of primary processes – fuel burning, gas compression and expansion, heat and mass transfer – as well as equations for calculating physical and chemical properties of working substances. Mathematical model includes inequalities which account for restriction of process parameters and restrictions of defining dimensions for various types of equipment – GTU, air coolers, heat exchangers, vaporizers and gas coolers. Our method of calculation of GTU parameters for variable operation modes is based on generalized characteristics presented in relative reduced form.

The model has been applied for designed equipment (WHB, air coolers, heat exchangers) models (Computer software No 2011616340, 2012613266, 2012613267, 2014660962). The block of evaluation of GTU operation parameters in variable modes implemented via spreadsheet software MS Excel 2013 includes structured nominal data for electric power generators of CCGT units and various types of GCU of compressor station.

After generalization of experimental data [8, 9], we have found the following calculated correlations between GTU reduced parameters in relative form:

– effective power – a function of temperature of combustion products at the inlet valve of turbine

$$\bar{N}_{er} = 1 - 4.2 \left(1 - T_{1r}\right) T_{1r}^{-1.24}$$

– rotor rotation frequency

$$\bar{n}_r = \bar{N}_{er}^{0.21}$$

– degree of pressure ratio in the compressor

$$\bar{\varepsilon}_k = \bar{N}_{er}^{0.42}$$

– mass air flow rate in the compressor

$$\bar{G}_{ar} = \bar{N}_{er}^{0.33}$$

– effective efficiency
\[ \eta_e = \frac{N_{er}}{1 - 0.75 \left(1 - \frac{N_{er}}{N_{er}}\right)}; \]

- fuel gas consumption rate

\[ \bar{G}_{fr} = 1 - 0.75 \left(1 - N_{er}\right); \]

- temperature of combustion products at the outlet valve of turbine

\[ T_{2r} = 1 - 0.165 \left(1 - N_{er}\right); \]

- temperature of air leaving the compressor

\[ T_{4r} = N_{er}^{0.133}. \]

The calculation module for GTU variable operation modes contains the following primary blocks:

- initial data block (ambient parameters, composition and pressure of fuel gas, nominal GTU parameters from structured data block);
- nominal parameters of Russian-produced GTU of various types and dimensions;
- reduced characteristics represented as diagrams and approximation correlations;
- calculation of combustion process characteristics;
- calculation of actual GTU parameters including engineering and economical characteristics.

Actual parameters are evaluated using correlations as follows:

\[ X = f\left[\bar{X}_r, X_0, \varphi\left(T_a, T_{a_0}, P_a, P_{a_0}\right)\right], \]

where \( \bar{X}_r, X_0 \) are actual, relative reduced and nominal values of the parameter; \( \varphi\left(T_a, T_{a_0}, P_a, P_{a_0}\right) \) is the correlation function between GTU parameter and ambient temperature and pressure for calculated or nominal operation modes.

Engineering and economic efficiency of GTU power stabilization system is determined by comparing its integral social and economic effect:

\[ \Delta I_{\Sigma} = \sum_{t=0}^{T} \left(\Delta I_{pr}^r + \Delta I_{c}^r\right) (1 + E)^{y_{opt} - t} + \Delta A_T (1 + E)^{-T} \]

where \( \Delta I_{pr}^r, \Delta I_{c}^r \) are, respectively, cost saving for production and consumption of electric and thermal power, fuel consumption, water supply and disposal during the \( t \)-th year of cost-effective unit operation compared to its basic variation (without cycled air conditioning in GTU and water production); \( \Delta A_T \) is the difference between depreciable cost of capital assets of the variation by the end of calculation period \( T \); \( E \) is the standard for reducing costs and effects to a single time; \( y \) is optimization variable.

4. Analysis of engineering and economic parameters of GCU power stabilization system

Let us review the primary engineering and economic parameters of GCU power stabilization system which include three GT8C2 type GTUs, three KU-93 type waste heat boilers and three K-6-2.4 KTZ type steam turbines.

Parametric analysis (see Table) has been performed in comparison to basic variation of GCU without cycled air cooling system for GTU and process water production. The variations have the same reliability of power supply for process loads during the \( t \)-th year of operation. Costs of additional
equipment installation to air preparation units and water coolers are determined in accordance with required total refrigerating capacity of vaporizers equal to 11 MW.

Table. Efficiency characteristics of CCGT:
1 – base version of CCGT; 2 – CCGT with the installation of power stabilization GTU.

| Index | 1  | 2 |
|-------|----|---|
| Power (MW): | | |
| electrical | 192 | 192 |
| thermal | 163 | 163 |
| Fuel rate to generate power: | | |
| electrical (tons of reference fuel/MW h) | 0.162 | 0.145 |
| thermal (tons of reference fuel/GJ) | 0.045 | 0.045 |
| Annual output of energy: | | |
| electrical (MW-h) | 1 549 008 | 1 562 400 |
| thermal (10^3 GJ) | 4875.9 | 4875.9 |
| Capital costs (%) | 100.0 | 100.8 |
| Annual operating costs for energy production and consumption, water consumption and wastewater disposal (%) | | |
| | 100.0 | 93.1 |
| Integral effect over 10 years (mil RUB) | 13263.2 | 13516.1 |
| Cost of production of energy: | | |
| electrical (RUB/kW-h) | 0.498 | 0.485 |
| thermal (RUB/GJ) | 138.7 | 136.4 |

As we can see, basic variation has lower capital costs. However, the total output of this variation is also lower. The cost-efficient variation of GCU is characterized by reduction of operational costs (no deductions for equipment depreciation and maintenance from capital costs) by almost 7%. The cost of production of heat and electric power for this variation is also lower compared to basic one which serves an indicator for expediency of installing GCU with GTU cycled air cooler and water production system for combined units.

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