Research on Thermodynamic Parameters of a Micro-Turbine for Standalone Cogeneration

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Abstract. In order to advance the heating and hot water systems in the Russian Federation we need to address the problem of introducing new sources of heat and electric energy. The paper overviews the relationship between the reliability, efficiency and diagnostic maintenance of the GMTU, the studies of rated and operating conditions of the GMTU, the development and improvement of methods for calculating rated and operating thermodynamic and diagnostic parameter of the unit. This resulted in developing a passport of thermodynamic parameters that can be compared to the parameters of the same units when they operate for the purpose of diagnosing their state.

1. Introduction
The American firm Capstone indirectly introduces gas micro-turbines of the centrifugal type for combined production of heat and electricity. In the near future, as a result of import substitution, they can play the role of a new driving force in the evolution of engineering systems for decentralized production of electricity and heat (cogeneration).

Micro-turbines can create a reliable, year-round cogeneration for power of both sports, shopping, social facilities, and oil and gas facilities, such as compressors, pumping stations and oil and gas processing plants [1].

2. Research
The object of this research is equipment in the winter sports center "Pearl of Siberia" located 50 km from the city of Tyumen - gas micro-turbine units (GMTU).

The subject of this research is cogeneration processes in the GMTU CapstoneC65. The objective is development of algorithms for determining the parameters of control and diagnostic of operation modes and the technical state of the GMTU.

Figures 1 and 2 show a micro-turbine in the section and its exterior.
Operating modes are clustered and standalone. The article presents the results of the research on a standalone operating mode of micro-turbines.

A thermotechnical scheme of a unit with rated parameters is shown in Figure 3. Here are given rated (passport) temperature values for air and combustion products at the inlet and outlet of the generator, the centrifugal compressor and turbine, the combustion chamber and the integrated recuperator for heating the air entering downstream of the compressor into the combustion chamber.
Figure 3. A thermotechnical scheme of the GMTU.

Figure 4 shows a device of the heat exchanger designed for heating water of the heat supply or hot water supply systems. Heating is provided by heat transfer from the combustion products through the walls of the ribbed tube heat exchanger to the water [2, 3].

Figure 4. A scheme of the main components of the heat exchanger.
More information on the rated specifications of micro-turbines is presented in Table 1.

Table 1. Rated specifications of the GMTU.

| Parameter                                      | Notation | Units | Value |
|------------------------------------------------|----------|-------|-------|
| Ambient air temperature                        | $T_a$    | K     | 288   |
| Ambient air pressure                           | $P_a$    | kPa   | 101.33|
| Effective capacity                             | $N_e$    | kW    | 65    |
| Mass air flow:                                 |          |       |       |
| into the combustion chamber (CC)               |          |       |       |
| for cooling the CC                             |          |       |       |
| total, through the centrifugal compressor      | $M_{air}$| kg/s  | 0.633 |
| Air temperature upstream the centrifugal compressor | $T_o$   | K     | 783   |
| Air temperature downstream the centrifugal compressor | $T_e$   | K     | 478   |
| Air temperature downstream the recuperator     | $T_v$    | K     | 783   |
| Temperature of combustion products upstream the PT | $T_z$   | K     | 1227  |
| Temperature of combustion products downstream the PT | $T_s$   | K     | 908   |
| Temperature of combustion products downstream the recuperator | $T_s$   | K     | 577   |
| Mass flow of combustion products               | $M_{CP}$ | kg/s  | 0.49  |
| Mass flow of the fuel gas                      | $B$      | kg/s  | 0.0047|
| Net calorific value of the fuel gas            | $Q_n^p$  | kJ/kg | 47590 |
| Effective efficiency of the GMTU               | $\eta_e$ | -     | 0.29  |
| Combustion chamber efficiency                  | $\eta_{CC}$ | - | 0.98  |
| Shaft rotation frequency                       | $n$      | s $^{-1}$ | 1600 |

To calculate the additional rated characteristics of the unit we developed an algorithm that includes the sequence of known thermodynamic equations for calculating gas turbine units [4]. The algorithm is shown below.

The algorithm for calculating the additional rated characteristics of the GMTU

$$L_o = \frac{Q_n^p}{2900}.$$  \hspace{1cm} (1)

$$\alpha = \frac{\eta_{CC} \cdot Q_n^p}{L_o \cdot C_p \cdot (T_z - T_v)}.$$  \hspace{1cm} (2)
\[ N_{PT} = M_{CP} \cdot C_{pT} \left( T_z - T_s \right), \]  \hfill (3)  
\[ N_C = M_{air} \cdot C_{pT} \left( T_c - T_{a} \right), \text{ kW}. \]  \hfill (4)  
\[ N_{AG} = N_{PT} - N_C, \text{ kW}. \]  \hfill (5)  
\[ \delta_{N_e} = \frac{N_{AG} - N_e}{N_{AG}} \cdot 100, \text{ %}. \]  \hfill (6)  
\[ \eta_{CC} = 0.98. \]  \hfill (7)  
\[ \eta_{AG} = \frac{N_{AG}}{Q^p \cdot B}. \]  \hfill (8)  
\[ \delta_{\eta_e} = \frac{\eta_{AG} - \eta_e}{\eta_{AG}} \cdot 100, \text{ %}. \]  \hfill (9)  
\[ P_c = P_o \left( \frac{T_c}{T_o} \right)^{\frac{k}{k-1}}, \text{ kPa}. \]  \hfill (10)  
\[ P_z = P_c \cdot \sigma_{CC}, \text{ kPa}. \]  \hfill (11)  
\[ \varepsilon_C = \frac{P_c}{P_o}. \]  \hfill (12)  
\[ \lambda_{PT} = \frac{P_z}{P_s}. \]  \hfill (13)  
\[ \varphi = \frac{T_v - T_c}{T_s - T_c}. \]  \hfill (14)  
\[ C_p = A + t \cdot 9.355 \cdot 10^{-5} + t^2 \cdot 3.694 \cdot 10^{-7} - t^3 \cdot 2.769 \cdot 10^{-10}, \text{ kJ/kg} \cdot \text{K}. \]  \hfill (15)  

Table 2 shows the results of calculating the additional rated characteristics of the unit such as: stoichiometric ratio (amount of air per 1 kg of fuel); excess air ratio; power generated by the PT; power consumed by the centrifugal compressor; air pressure behind the centrifugal compressor; pressure of combustion products upstream the PT; degree of regeneration. Completion of the full calculation of the rated operating mode allowed us to create a passport on thermodynamic parameters that is compared to the operating parameters of the same unit to diagnose its modes of operation and technical state.
Table 2. The results of calculating the additional rated characteristics of the GMTU.

| №  | Parameter                                           | Notation | Units     | Value    |
|----|-----------------------------------------------------|----------|-----------|----------|
| 1  | Stoichiometric ratio                                | $L_0$    | kg/kg     | 16.41    |
| 2  | Excess air ratio                                     | $\alpha$ |           | 5.38     |
| 3  | Heat capacity of combustion products for the CT     | $C_{pr}$ | kJ/kg·K   | 1.189    |
| 4  | Power generated by the PT                            | $N_{PT}$ | kW        | 190.54   |
| 5  | Heat capacity of air for the centrifugal compressor | $C_{Pair}$ | kJ/kg·K | 1.043   |
| 6  | Power consumed by the centrifugal compressor        | $N_c$    | kW        | 125.54   |
| 7  | Calculated effective capacity of the GMTU           | $\delta_{N_c}$ | %    | 0        |
| 8  | Calculation error $N_e$                             | $\delta_{N_e}$ | %    | 0        |
| 9  | Combustion chamber efficiency                       | $\eta_{CC}$ | %    | 0.98     |
| 10 | Effective efficiency of the GMTU                    | $\delta_{\eta_e}$ | %    | 29       |
| 11 | Calculation error $\eta_e$                          | $\delta_{\eta_e}$ | %    | 0        |
| 12 | Air pressure behind the centrifugal compressor      | $P_c$    | kPa       | 573.1    |
| 13 | Pressure of combustion products upstream the PT      | $P_z$    | kPa       | 555.9    |
| 14 | Indicator of adiabatic expansion process of         | $\kappa_T$ | -    | 1.2855   |
|    | combustion products in the PT                        |          |          |          |
| 15 | Degree of increase in air pressure in the            | $\varepsilon_C$ | -    | 5.89     |
|    | centrifugal compressor                              |          |          |          |
| 16 | Expansion ratio of combustion products in the PT     | $\lambda_{PT}$ | -    | 3.88     |
| 17 | Degree of regeneration                              | $\varphi$ | -    | 0.71     |

Below shows presents the developed algorithm for calculating the operating modes for different loads from 25 to 100 percent of the nominal value. The calculation results are presented in Table 3. During operation of micro-turbines the number of controlled operating mode parameters is limited and presented in Table 3 as power coefficients of the centrifugal compressor and the PT; temperature coefficients of the PT and the centrifugal compressor; temperatures of air and combustion products downstream the PT. Completion of the full calculation of variable operating modes of the unit allowed us to create a passport on thermodynamic parameters that is compared to the operating parameters of the same unit under the load of 25 to 100 percent of the nominal value to diagnose its modes of operation and technical state by comparison.

The algorithm for calculating the operating characteristics of the GMTU

$$\varphi_C = \frac{N^H_e}{N^H_C}.$$  \hspace{1cm} (16)

$$\varphi_{CT} = \frac{N^H_e}{N^H_{CT}}.$$  \hspace{1cm} (17)
\[ \varphi_{CT} = \frac{T_T}{T_S} \]  \hfill (18)  
\[ \varphi_{TC} = \frac{T_C}{T_T} \]  \hfill (19)  
\[ N^P_C = \frac{N^p_e}{\varphi_C}, \text{ kW} \]  \hfill (20)  
\[ M^F_{AIR} = \frac{N^F_C}{C_{P,air} (T^p_C - T^p_o)}, \text{ kg/s.} \]  \hfill (21)  
\[ N^F_{CT} = \frac{N^p_e}{\varphi_{CT}}, \text{ kW.} \]  \hfill (22)  
\[ M^F_{CP} = \frac{N^F_C}{C_{P,CP} (T^p_C - T^p_S)}, \text{ kg/s.} \]  \hfill (23)  
\[ T^p_v = \varphi \cdot (T^p_S - T^p_C) + T^p_C, \text{ K.} \]  \hfill (24)  
\[ \alpha^F = \frac{\eta_{CC} \cdot Q^p_H}{L_o \cdot C_p (T^p_C - T^p_v)}. \]  \hfill (25)  
\[ B = \frac{M^F_{CC}}{\alpha^F L_o}. \]  \hfill (26)  
\[ \epsilon_C = \left( \frac{T^p_C}{T^p_0} \right)^{k-1}. \]  \hfill (27)  
\[ \epsilon_{CT} = \left( \frac{T^p_T}{T^p_S} \right)^{k_t-1}. \]  \hfill (28)  

**Table 3.** Initial data for various operating modes of the GMTU.

| № | Parameters                              | Notation | Units | Power, kW |
|---|----------------------------------------|----------|-------|-----------|
| 1 | Capacity of the GMTU                  | \( N^p_e \) | kW   | 16.25 32.5 56.23 65 |
|   | Rated power factor of the              | \( \varphi_C \) | -    | 0.5178 0.5178 0.5178 0.5178 |
|   | centrifugal compressor CT              | \( \varphi_{CT} \) | -    | 0.3411 0.3411 0.3411 0.3411 |
| 2 |                                        |          |       |           |
Table 4 shows the main results of calculating the operating modes of Capstone C65.

### Table 4. The results of calculating the operating modes of Capstone C65.

| № | Parameters                                           | Units | Power, kW |
|---|------------------------------------------------------|-------|-----------|
|   |                                                      |       | 0.25 \( N_F \) | 0.50 \( N_F \) | 0.865 \( N_F \) | \( N_F \) |
| 1 | Actual capacity of the CT centrifugal compressor     | kW    | 29.45     | 62.77     | 108.63    | 125.53    |
| 2 | Air temperature downstream the centrifugal compressor| K     | 413.3     | 431.7     | 459.0     | 478.0     |
| 3 | Average air temperature in the centrifugal compressor| °C    | 79.15     | 86.85     | 100.50    | 110.00    |
| 4 | Average heat capacity of air                         | kJ/kg·K | 1.040     | 1.042     | 1.044     | 1.045     |
| 5 | Air flow of the centrifugal compressor               | kg/s  | 0.2412    | 0.4193    | 0.6090    | 0.6322    |
| 6 | Actual capacity of the CT                            | kW    | 47.64     | 95.28     | 164.91    | 190.56    |
| 7 | Temperature of combustion products                   | K     | 1061.0    | 1108.0    | 1152.6    | 1226.9    |
| 8 | Temperature of combustion products                   | K     | 785       | 820       | 853       | 908       |
| 9 | Average temperature in the CT                        | °C    | 650.0     | 691.0     | 729.8     | 794.5     |
| 10| Average heat capacity of the CT                      | kJ/kg·K | 1.17      | 1.18      | 1.19      | 1.21      |
| 11| Flow of combustion products in the CT                | kg/s  | 0.1470    | 0.2804    | 0.4625    | 0.4930    |
| 12| Air temperature downstream the recuperator           | K     | 677       | 707       | 738       | 783       |
| 13| Average temperature at \( T_z \) and \( T_v \)      | °C    | 596.0     | 634.7     | 672.3     | 732.0     |
|   | Excess air ratio | $\alpha^F$ | 6.38 | 6.06 | 5.81 | 5.38 |
|---|-----------------|----------|------|------|------|------|
| 15 | Flow of the fuel gas | $B^F$ kg/s | 0.00151 | 0.00277 | 0.00420 | 0.00470 |
| 16 | Degree of pressure increase | $\varepsilon_C$ | 3.50 | 4.12 | 5.11 | 5.89 |
|     | Expansion ratio of combustion products in the CT | $\lambda_{CT}$ | 3.88 | 3.88 | 3.88 | 3.88 |

### 3. Conclusion
The studies and the results of calculations on the nominal operating parameters and operating modes of the GMTU allow us to create a passport of thermodynamic characteristics that, when compared to the parameters of the same units in operation, become diagnostic features. Furthermore, based on the results obtained design solutions can be taken on the development of systems with alternative sources of heat and power (cogeneration), for example when APG is used as a fuel.

### References:
[1] Zemenkov Yu D 2015 *Design and operation of gas turbine units* Reference manual ed by Yu D Zemenkov (Tyumen; TyumGNGU) 434
[2] Zemenkov Yu D 2015 *Heat and mass transfer equipment and thermal processes in the transport and storage of oil and gas production systems* Reference manual ed by Yu D Zemenkov (Tyumen; TyumGNGU) 175
[3] Moiseev B V, Zemenkov Yu D and Toropov S Yu 2014 *Industrial power system* Reference manual (Tyumen; TyumGNGU)
[4] Ilyuhin K N, Shapoval A F, Chekardovskiy S M Organization of control and diagnostics of equipment in the system of heat and gas supply *Collection of materials of scientific-practical conference dedicated to the 30th anniversary of the TyumGASA* (Moscow)182-5
[5] Zemenkov, Yu.D., Shalay, V.V., Zemenkova, M.Yu. (2015) Expert Systems of Multivariable Predictive Control of Oil and Gas Facilities Reliability. Procedia Engineering, Volume 113, pp.312-315 DOI: 10.1016/j.proeng.2015.07.271
[6] Zemenkov, Yu.D., V.V. Shalay, M.Yu. Zemenkova. Immediate Analyses and Calculation of Saturated Steam Pressure of Gas Condensates for Transportation Conditions (2015) Procedia Engineering, Volume 113 (2015), pp. 254-258 doi:10.1016/j.proeng.2015.07.330