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Methods for Determining the Thermodynamic Parameters of Gas Compressor Units of Main Gas Pipelines

M N Chekardovskiy, S M Chekardovskiy and K N Ilyukhin

Industrial University of Tyumen, 38 Volodarskogo st., Tyumen, 625000, Russia

E-mail: zemenkov@tsogu.ru

Abstract. Methods for evaluating the state of gas compressor units of main gas pipelines by the values of the thermodynamic parameters measured during operation, that is indirectly, should be developed. In this regard the authors have conducted a comparative analysis of various techniques. Based on the results conclusions have been made on how to develop the thermodynamic method of diagnosis.

1. Introduction

During operation of gas compressor units of main gas pipelines (further on – GCU of MGP) the equipment is gradually deteriorating because of natural wear-out. Therefore, the development of efficient methods for determining the technological and diagnostic GCU parameters during operation, identification of defects at an early stage of their occurrence is a very urgent problem, which is complicated by a great variety of automatic data collection and management systems for nominally controlled parameters. Given the complexity of the processes occurring in GCU it is necessary to develop specific diagnostic methods for further application in complex systems to optimize the maintenance and repair of units that will lead to the improvement of quality, reliability and efficiency of GCU of MGP. One of the most promising methods for determining the technological and diagnostic parameters of GCU is the thermodynamic method. This is due to the current lack of sensors that allow one to directly determine the technical condition of the GCU elements (erosion of centrifugal blower impellers, radial clearance of turbines, combustion chambers burnouts and others). Such sensors may never appear due to their complexity, uniqueness (depending on the design of a unit), and high cost. It is necessary to develop methods for assessment of the GCU technical condition by the values of process parameters measured directly during operation, that is, indirectly. For this purpose, a comparative analysis of different techniques for determining the main thermodynamic parameters (TDP) was conducted. Based on the results we made our conclusions on the direction of the thermodynamic method development.

2. Research

In the system approach to developing diagnostic techniques based on the thermodynamic method, in most cases, a GCU as a diagnostic object is divided into elements according to their functions and processes:

1. gas turbine unit (GTU) compressor;
2. GTUcombustion chamber (CC);
3. GTUturbine;
4. gas blower or compressor;
5. GTU recuperator;
6. exhaust gas heat exchanger of GTU.

The mathematical apparatus of the thermodynamic method makes it possible to explore the parameters of GCU both element by element, and as a whole as a single object, ie to solve problems of integral and differential diagnosis.

Calculating the integral TDP by various techniques, such as the effective power (N_e) and the effective efficiency of the unit (η_e) is performed for six units GTK-10-4 with a blower 370-18-1. Techniques were used based on the TDP calculations of the following authors: Zarickiy S. P., Lopatin A. S., Porshakov B. P., Ryabchenko A. S., Stepanov O. A., Chekardovskiy M. N., Shabarov A. B. Calculation of parameters was carried out in order to compare and identify their strengths and weaknesses in the practice of diagnosing gas compressor units. Figure 1 provides the design scheme. The design scheme shows basic structural elements of the GCU and the parameters measured in units using both regular equipment, and specially installed instrumentation required to obtain sufficient initial information used in computational methods. A more detailed description of the scheme is given below.

From the suction chamber air is taken with the parameters $T_a$and P_a, which are recorded by regular devices. Before the first step of the axial compressor (AC) there is a slight change in the intake air parameters to the level of T_0, P_0. In the AC the air is compressed and acquires the output parameters T_C, P_C, which are recorded by regular devices. Compressed air is supplied to the heat exchanger (recuperator) and heated to a temperature T_v, pressure is P_v. The compressed and heated air enters the combustion chamber where it is mixed with the fuel gas, which is supplied through a separate fuel line. The fuel gas parameters T_d, P_d, ΔP are recorded by additional devices. The combustion products after the CC enter the HP turbine with the parameters T_Z and P_Z. T_Z is calculated, P_Z is recorded by regular devices. The temperature of the combustion products ($T`_S$) between the HP turbine and the LP turbine is calculated. The combustion products at the LP turbine outlet have the parameters T_S and P_S recorded by regular devices. In addition, a flow meter for combustion products is installed, which records ΔP in the gas duct before the recuperator. Via the blower, regular devices record the gas parameters T_1, P_1 and T_2, P_2, as well as the rotor speed of the blower $n = n_{ТНД}$ and the AC rotor ($n_{ОК} = n_{ТВД}$). The composition of the transported gas components according to the CC data is given in table 1.

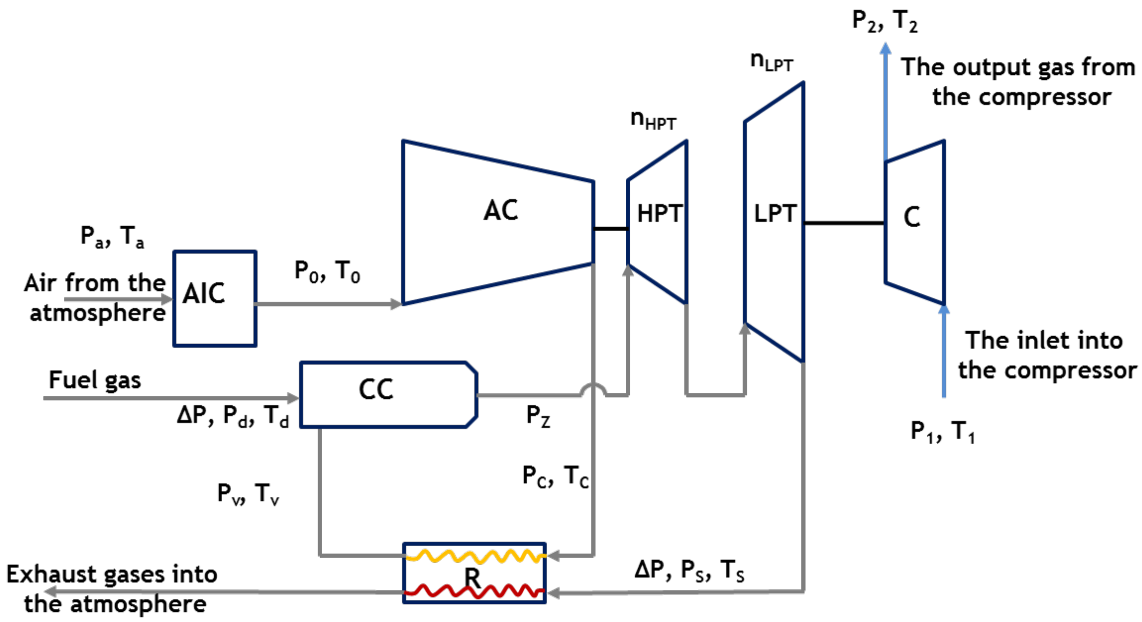

Figure 1. Schematic diagram of the initial data collection by the TDP

In the studies were used data on the composition and characteristics of the natural gas components of the Urengoiskoye field and the initial data by the TDP - GTK-10-4 at the Bogandinskaya CS.

Techniques for TDP calculation:

1. Calculation of the TDP based on the technique by Chekardovskiy M. N. and others. (Technique 1)

Sequence of calculating Ne and ηe [4]:

Using the initial data from tables 1 and 2 let us calculate the following characteristics of the gas by the equations [2]:

$$\mu_m = \frac{1}{100} \cdot \sum r_i \cdot \mu_i \tag{1.1}$$

Elemental fuel weight composition in percentages:

$$C^P = \frac{12.01}{\mu_m} \cdot \left(r_{C_1} + 2r_{C_2} + 3r_{C_3} + 4r_{C_4} + r_{CO_2}\right) \tag{1.2}$$

$$H^P = \frac{1.008}{\mu_m} \left(4r_{C_1} + 6r_{C_2} + 8r_{C_3} + 2r_{H_2S}\right) \tag{1.3}$$

$$S^P = \frac{32.06}{\mu_m} r_{H_2S} \tag{1.4}$$

$$N^P = \frac{28.016}{\mu_m} r_{N_2} \tag{1.5}$$

$$O^P = \frac{32}{\mu_m} r_{CO_2} \tag{1.6}$$

where C^P, H^P, S^P, N^P, O^P – weight concentration of, respectively, carbon, hydrogen, sulfur, nitrogen, oxygen.

$$E = \frac{12.01 \cdot H^P + 0.126 \cdot O^P}{4.032 \cdot C^P + 0.3755 S^P} \tag{1.7}$$

$$L_0 = 0.1151 \cdot (1 + E) \cdot C^P \tag{1.8}$$

$$Q_H^P = \frac{\sum r_i \cdot Q_i}{100 \cdot \mu_m} \tag{1.9}$$

$$R = \frac{8.314}{\mu_m} \tag{1.10}$$

The density of the combustion products behind the LP turbine:

$$P_S = P_a + P_{exc} \tag{1.11}$$

left gas duct

$$\rho_L = \rho_{15} \cdot \frac{P_S \cdot 288}{98.1 \cdot T_S} \tag{1.12}$$

right gas duct

$$\rho_R = \rho_{15} \cdot \frac{P_S \cdot 288}{98.1 \cdot T_S} \tag{1.13}$$

The consumption of combustion products:

$$M_{CP_L} = F_L \cdot \sqrt{2 \cdot \Delta P_L \cdot 10^6 \cdot \rho_L} \tag{1.14}$$

$$M_{CP_R} = F_R \cdot \sqrt{2 \cdot \Delta P_R \cdot 10^6 \cdot \rho_R} \tag{1.15}$$

$$M_{CP} = M_{CP_R} + M_{CP_L} \tag{1.16}$$

$$M_{AIR} = M_{CP} - B \tag{1.17}$$

$$\alpha = \frac{M_{AIR}}{B \cdot L_0} \tag{1.18}$$

$$C_{P_{AIR}} = 0.9379 + 0.000198 \cdot \frac{T_S + T_C}{2} \tag{1.19}$$

Let us determine the temperature of the combustion products before the HP turbine:

$$T_Z = \frac{0.98 \cdot Q_H^P + C_{P_{AIR}} \cdot (\alpha \cdot L_0 \cdot T_v + T_0)}{C_{P_{AIR}} \cdot (\alpha \cdot L_0 + 1)} \quad (1.20)$$

The capacity of the axial compressor:

$$N_{AC} = M_{AIR} \cdot C_{P_{AIR}} \cdot (T_C - T_0) \quad (1.21)$$

The capacity of the high pressure turbine on condition that the HP turbine and the AC are on the same shaft [1]:

$$N_{HPT} = 1.015 \cdot N_{AC} \quad (1.22)$$

The temperature of the combustion products behind the HP turbine:

$$C_{P_{CP}} = 0.9796 + 0.000283 \cdot \frac{T_S + T_C}{2} \quad (1.23)$$

$$T`_S = T_Z - \frac{N_{HPT}}{M_{CP} \cdot C_{P_{CP}}} \quad (1.24)$$

The effective capacity of the GCU:

$$N_e = M_{CP} \cdot C_{P_{CP}} \cdot (T`_S - T_S) \quad (1.25)$$

The effective efficiency of the GCU:

$$\eta_e = \frac{N_e}{B \cdot Q_P^H} \quad (1.26)$$

2. Calculation of the TDP based on the technique by Shabarov A. B. (Technique 2)

Sequence of calculating N_e and η_e [5]:

Using the data in Table 3.2 let us determine the absolute pressure of the combustion products behind the LP turbine:

$$P_T = \frac{P_{S_R} + P_{S_L}}{2} \quad (2.1)$$

The expansion ratio of the combustion products in the turbine:

$$\pi_T = {P_G}/{P_T} \quad (2.2)$$

To calculate the temperature of the combustion products before the HP turbine let us take k = 1.33 [1]:

$$T_G = \frac{T_T}{1 - \left(1 - \pi_T^{\frac{1-k}{k}}\right) \cdot \eta_L} \quad (2.3)$$

By (1.19) and (1.23) let us find the heat capacity of the air and combustion products C_{Pair} and C_{PG} correspondingly, at temperatures T_P and T_G, then determine the relative fuel consumption and air consumption:

$$g_f = \frac{C_{P_G} \cdot T_G - C_{P_в} \cdot T_P}{Q_H^P \cdot G_f - \left(C_{P_G} \cdot T_G - C_{P_G} \cdot T_O\right)} \quad (2.4)$$

$$G_{AIR} = {G_f}/{g_f} \quad (2.5)$$

To determine the specific work of the compressor and the turbines by (1.19) and (1.23) us find the heat capacity of the air and combustion products C_{Pair} and C_{PG} correspondingly, within the predetermined temperature range: T_C, T_a (for the air in the compressor) and T_G, T_S (for the combustion products in the turbines):

$$L_{AC} = C_{Pair} \cdot \left(T_{AC} - T_a\right) \quad (2.6)$$

$$L_T = C_{P_G} \cdot (T_G - T_T) \tag{2.7}$$

The effective capacity of the GCU:

$$N_e = L_T \cdot (G_f + G_{AIR}) \cdot \eta_M - L_{AC} \cdot G_{AIR} \tag{2.8}$$

To calculate the effective efficiency of the GCU let us determine the specific power and specific fuel consumption:

$$N_{e\,sp} = N_e / G_{AIR} \tag{2.9}$$

$$C_e = \frac{3600 \cdot g_m}{Ne_{sp}} \tag{2.10}$$

Note: Q_H^P is taken from the results of the calculation technique 1:

$$\eta_e = \frac{3600}{C_e \cdot Q_H^P} \tag{2.11}$$

3. Calculation of the TDP based on the technique by Porshakov B. P. (Technique 3).

Sequence of calculating N_e and η_e [6]:

Using the equations from technique 1 and the data in tables 1 and 2 let us calculate the change in enthalpy during the compression of gas in the blower:

$$C = 360 - \frac{(66 \cdot r_{CH_4})}{100} \tag{3.1}$$

$$\Delta C_P = \frac{6 \cdot C \cdot P_1 \cdot 10^3}{\left(\frac{T_1 + T_2}{2}\right)^3} \tag{3.2}$$

$$C_{P_0} = 4.187 \cdot \left(0.334 + \frac{0.66 \cdot r_{CH_4}}{100}\right) \cdot \left(0.519 + 0.000583 \cdot \left(\frac{(T_1 + T_2) - 546}{2}\right)\right) \tag{3.3}$$

$$\Delta h = (C_{P_0} + \Delta C_P) \cdot (T_2 - T_1) \tag{3.4}$$

Let us find the effective capacity of the GCU, the nameplate capacity and the technical condition factor of the GCU:

$$N_e = \sum_{j=1}^{n} b_j \left(\frac{\Delta h}{60}\right)^{j-1} \cdot \rho_C \cdot \left(\frac{n}{n_{nom}}\right)^3 + N_M \tag{3.5}$$

$$N_{e\,pr} = N_{e\,nom} \cdot \left[1 - 4.2 \cdot \left(1 - \frac{T_Z \cdot T_{anom}}{T_{Z_{nom}} \cdot T_a}\right) \cdot \frac{T_Z \cdot T_{a_{nom}}}{T_{Z_{nom}} \cdot T_a}\right] \cdot \frac{P_a}{P_{a_{nom}}} \cdot \sqrt{\frac{T_a}{T_{a_{nom}}}} \tag{3.6}$$

$$k_{\text{GCU}} = N_e / N_{e\,pr} \tag{3.7}$$

The effective efficiency of the GCU determined by the heat received from the combustion of fuel, taking into account the technical condition factor:

$$B \cdot Q_H^P = \frac{0.25 \cdot [1 + (1 - k_{ГТУ}) \cdot C`]}{\eta_{e_{НОМ}}} \left(N_{e\,НОМ} \cdot \frac{P_a}{P_{a_{НОМ}}} \cdot \sqrt{\frac{T_a}{T_{a_{НОМ}}}} + 3 \cdot N_e\right) \tag{3.8}$$

$$\eta_e = \frac{N_e}{B \cdot Q_H^P} \tag{3.9}$$

4. Calculation of the TDP based on the techniques by Zarickiy S. P. (Technique 4A, 4B)

Sequence of calculating N_e and η_e (variants A and B) [3]:

Variant A.

The expansion ratio of the combustion products in the turbines, necessary for determining the power parameter B, is determined by the following formula similar to (2.2):

$$\varepsilon_T = P_Z / P_S \tag{4.1}$$

By [3] let us determine B depending on ε_T and calculate the effective capacity:

$$N_e = B \cdot P_S \cdot 101971 \cdot \sqrt{T_S} \tag{4.2}$$

The effective efficiency is determined by (1.26), using the missing data from technique 1 (B, Q_H^P):

$$\eta_e = N_e / B \cdot Q_H^P \tag{4.3}$$

Variant B.

Let us determine the factor K by the following formula, where P_{HOM} and T_{HOM} – the pressure and temperature under normal conditions:

$$K = 1.0164 \cdot \left(\frac{P_a}{P_{HOM}} \right)^{1.5} \cdot \left(\frac{T_a}{T_{HOM}} \right)^{0.5} \tag{4.4}$$

$$N_e = A \cdot K \cdot (101936 \cdot \Delta P_K)^{1.5} \tag{4.5}$$

$$\eta_e = N_e / B \cdot Q_H^P \tag{4.6}$$

5. Calculation of the TDP based on the technique by Shapoval Yu. A. (Technique 5)

Sequence of calculating N_e and η_e [2]:

The effective capacity and the effective efficiency are calculated as follows:

$$N_e = N_{eHOM} \cdot \left(\frac{n}{n_{HOM}} \right)^3 \tag{5.1}$$

Note: missing data are taken from technique 1 (B, Q_H^P).

$$\eta_e = N_e / B \cdot Q_H^P \tag{5.2}$$

Comparison of the techniques for calculating the TDP for the purpose of diagnosing the technical condition of the GCU is given below.

The results of calculations by techniques 1, 2, 3, 4, 5 are given in table 1[7].

Table 1. Results of calculations.

Unit №		1	2	3	4	5	6
Parameter	Unit of measurement	Values					
Technique 1							
N_e	kW	7895	7882	7263	6304	8585	9763
η_e		0.287	0.289	0.268	0.227	0.266	0.285
Technique2							
N_e	kW	6471	5856	6184	6724	8521	9282
η_e		0.234	0.214	0.228	0.241	0.263	0.271

Technique3							
N_e	kW	7279	7235	6545	6317	7126	9104
η_e		0.236	0.237	0.230	0.240	0.244	0.256
Technique4A							
N_e	kW	7510	6916	7560	7280	9473	9859
η_e		0.272	0.253	0.279	0.261	0.293	0.287
Technique4B							
N_e	kW	9077	8335	8430	8471	8885	9164
η_e		0.329	0.305	0.311	0.304	0.275	0.267
Technique5							
N_e	kW	7189	6990	6232	6795	7290	1000 0
η_e		0.260	0.255	0.230	0.244	0.225	0.292

To compare the techniques for calculating the TDP for the purpose of diagnosing the GCU we calculated deviations in the values of the effective capacity (table 2) and efficiency (table 3) of the units.

Table 2. Deviations in the values of the effective capacity of the GCU (kW) from the average value.

Techniques	Unit					
	1	2	3	4	5	6
1	324	679	226	-677	271	234
2	-1099	-1346	-851	-258	207	-246
3	-291	32	-490	-664	-1187	-424
4A	-60	-286	524	298	1160	330
4B	1506	1132	1394	1489	571	-364
5	-381	-212	-804	-187	-1023	471
Mean value	7570	7202	7036	6982	8313	9529

Table 3. Deviations in the values of the effective efficiency of the GCU (%) from the average value.

Techniques	Unit					
	1	2	3	4	5	6
1	1.64	2.95	1.02	-2.65	0.43	0.84
2	-3.52	-4.46	-2.96	-1.14	0.24	-0.56
3	-3.38	-2.20	-2.73	-1.32	-1.66	-2.03
4A	0.24	-0.58	2.12	0.85	3.19	1.12
4B	5.93	4.61	5.33	5.14	1,36	-0.90
5	-0.91	-0.31	-2.78	-0.88	-3.57	1.53
Mean value	27.0	25.9	25.8	25.3	26.2	27.7

3. Conclusion

From tables 2 and 3 we can see that for on-line determination of only N_e and η_e we should use technique 5, as it does not require any material expenses for carrying out the experimental work. Other techniques require additional installation and commissioning works to obtain the necessary initial data for individual nodes (AC, HP turbine, LP turbine, recuperator, centrifugal blower). The technique developed by the authors, if material expenses for installation and commissioning are available, provides data on individual elements of the GCU for monitoring and diagnosing their technical condition. Therefore, this development solves the problem of determining the technological and diagnostic parameters of the GCU during operation, identification of defects at an early stage of their occurrence.

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