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GAS-STEAM PLANTS, BASED ON GAS AND BACK-PRESSURE STEAM TURBINES

Technique for determination of basic indices of gas-steam turbines operation is suggested, dependences for their determination are built, variants of gas turbine superposed plants application at heat generation plants of industrial enterprises are considered.

Key words: *gas turbine, waste-heat boiler, back-pressure turbine, gas-steam plant.*

Introduction

Statistic data show that world consumption of electric energy in recent decade increased more than 30%. Forecast consumption of electric energy in Ukraine must increase 2.5 – 3 times as compared with 2005 [1]. Wear level of fixed assets of home heat power industry is more than 90% [2, 3]. Greater part of power-generating units at thermal power stations (TPS) of Ukraine not only exhausted their operation resource but 2 – 3 times exceeded it. Such power-generating units are characterized by high level of accident rate, low efficiency and must be withdrawn from operation. They can not be used for covering half peak and peak loads. According to the information of the Institute of coal technologies of National Academy of Science of Ukraine in 2010 7930 MW of installed capacity were not used in Ukraine. Two milliards $US annually must be spent during 20 years for modernization, reconstruction of existing and putting into operation of new power-generating units [3].

Predominant burning of coal at domestic power-generating units requires fulfillment of rigid ecological norms. By the information of International Atomic Energy Agency (IAEA), mortality rate in the regions where coal-fired thermal power stations operate is 10 times higher, than in the regions, where stations on gaseous fuel function. The necessity to solve ecological problems forced European Union to reduce considerably the consumption of coal. By 2030 half of the energy in the countries of Western Europe is planned to generate at electric stations, burning gaseous fuel.

Recently, the trend of decreasing single capacity of energy sources (distributed generation) appeared, the trend provides usage of large amount of small capacity power stations. Such electric stations with combined generation of energy must provide reliability and quality of energy supply in the given region, improve the efficiency of fuel usage and flexibility of energy system regulation. One of the directions of this strategy realization is application of gas turbine technologies.

Almost 70% of the increment of new energy generating capacities in the world is realized at the expense of gas-turbine units (GTU) of the simple cycle and steam-gas or gas-steam (GSU) units. Such units, as it is known, are characterized by high efficiency and flexibility in operation [4 – 7]. Gas turbines do not require large sites for deployment, they can operate on gaseous or liquid fuel, short term of putting into operation, have high specific capacity and high level of automation. Considering this, usage of natural gas cannot be the constraint for wide introduction of gas turbines. Ukraine is among 10 leading countries of the world, that have the complete cycle of the design and manufacturing of gas-steam units for energy branch of national economy. Necessary material base of GSU with electric powers of 2.5 – 135 MW and efficiency factor of up to 0.37 has been created.

The potential of GSU application for combined generation of heat and electric energy is generally recognized and is one of the components of the solution of the problem, dealing with the increase of electric generating capacities and energy conservation. Such GSU can be created by means of gas turbine superposed plants on numerous cogeneration plants of industrial enterprises, that supply steam to technological consumers, power and heat supply systems. Such cogeneration plants are equipped, as a rule, with back-pressure turbines, characterized by high energy efficiency and thermal capacity. Efficiency of GSU application on the base of condensing and extraction turbines is considered in [6, 7].

Taking into account the above-mentioned the problem was put forward to study the possibility of GSU application on the basis of the existing types of GTU and steam-turbine units (STU) with back pressure turbines and determine operation indices of such combined power units.

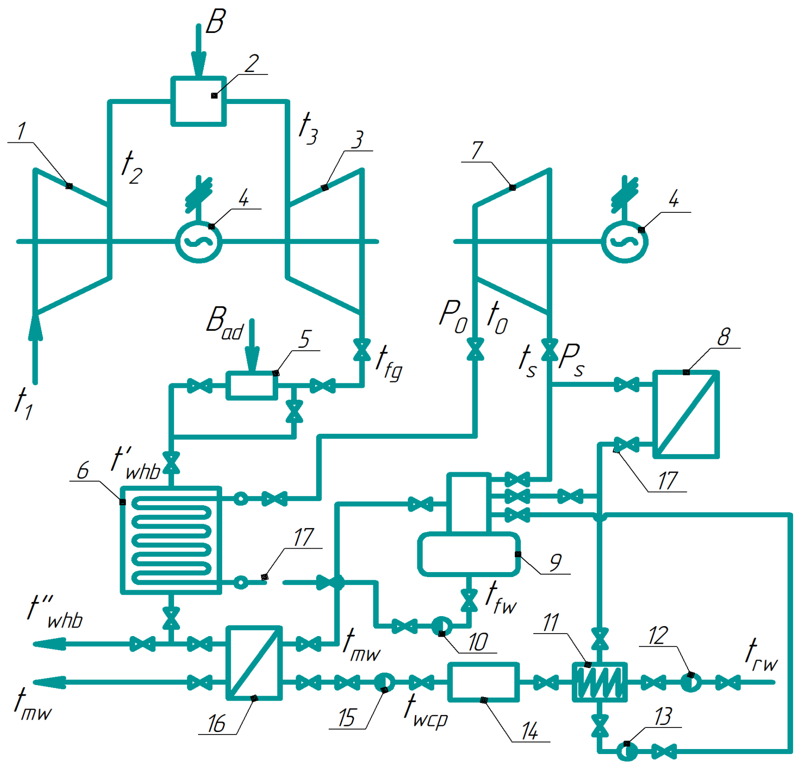

Fig. 1. Basic thermal block diagram of gas steam unit:
1 –compressor; 2 – combustion chamber; 3 –gas turbine; 4 –electric generator; 5 – block of additional combustion of fuel; 6 – waste-heat boiler; 7 – steam back-pressure turbine; 8 – steam consumers; 9 – deaerator; 10 –feed pump; 11 –raw water heater ; 12 –raw water pump; 13 – drain pump; 14 – water chemical purification (WCP); 15 – WCP pump; 16 – gas preheater of make-up water ; 17 – stop valves.

Main results

The following scheme of gas-steam units, created on the base of gas-turbine (GTU) and steam-turbine units (STU) (Fig. 1) is suggested. Gas-turbine unit (GTU) comprises: compressor 1; combustion chamber 2; gas turbine 3; electric generator 4;block of additional combustion of fuel 5; waste-heat boiler 6; gas preheater of make-up water 16. Block of additional combustion of fuel (BACF) serves for the increase of the temperature of gases, exhausted in gas-turbine unit (GTU) t_{ex} to the temperature t'_{whb} at the inlet in waste-heat-boiler, if it is necessary. Steam of certain pressure P_0 and temperature t_0 is generated in waste-heat boiler. Gas preheater is intended for heating of make-up water from water chemical purification in case of incomplete return of recycled condensate from technological consumers of steam 8. Thermal scheme of steam turbine unit (STU) consists of back-pressure turbine 7; electric generator 4; steam consumers 8; deaerator 9; feed pump 10; raw water heater 11; raw water pump 12; drain pump 13; water chemical purification 14; WCP pump 15. Temperatures in character points are marked on the scheme.

Manufacturer warranty characteristics of certain types of GTU are given in Table 1, characteristics of back-pressure turbines of small capacity – in Table 2.

Table 1

Characteristics of gas-turbine units

Indices	Type of GTU or motor							
	ГПА-12	ГТГ-16	ГТ-20	ГТД-25	НК-37-1	ГТД-45	ГТД-60	ГТГ-110
Electric power, MW	12	17	20	27.5	30	45	60	110
Temperature of gases in front of the turbine, °C	1080	1070	1250	1250	1220	1170	1170	1210
Degree of pressure increase	15.8	20	21	21.8	23.4	15	15	14.7
Temperature of gases after the turbine, °C	450	420	520	490	455	490	490	517
Efficiency factor	0.34	0.355	0.365	0.36	0.37	0.35	0.35	0.36
Equivalent fuel consumption, кg/s	1.204	1.634	1.870	2.607	2.760	4.388	5.850	10.428

Table 2

Characteristics of back-pressure turbines

Indices	Type of steam turbine										
	Р-1,5-15/3	Р-1,5-15/6	Р-2,5-15/3	Р-2,5-15/6	Р-2,5-35/3	Р-2,5-35/6	Р-4-35/3	Р-4-35/6	Р-6-35/3	Р-6-35/6	Р-12-35/5
Electric power, MW	1.5	1.5	2.5	2.5	2.5	2.5	4	4	6	6	12
Steam parameters in front of the turbine: pressure, MPa	1.47	1.47	1.47	1.47	3.43	3.43	3.43	3.43	3.43	3.43	3.43
temperature, °C	350	350	350	350	435	435	435	435	435	435	435
enthalpy, kJ/кg	3150	3150	3150	3150	3305	3305	3305	3305	3305	3305	3305
Steam temperature in back-pressure, °C	190	260	193	256	200	250	192	247	186	244	224
Steam enthalpy in back-pressure, kJ/kg	2845	2978	2831	2970	2866	2958	2830	2950	2837	2945	2907
Steam discharge per turbine, t/hr	21.8	35.2	34.3	63	29.2	32.6	35.6	44.8	50.5	66.6	114.7

Equivalent fuel consumption at GTU is determined by the formula, кg/s

$$B = N_g/(\eta_g \cdot Q_{eg}) = N_g/(\eta_g \cdot 29.3) = 0.03413\, N_g/\eta_g\,, \qquad (1)$$

where N_g – electric power of GTU, MW; η_g – efficiency of GTU; Q_{eq} – 29.3 MJ/kg – heat of combustion of equivalent fuel.

Power of gases, exhausted in GTU, MW

$$Q_{fg} = (G_g \cdot Cp_g \cdot t_{fg}) \cdot 10^{-3} = N_g \cdot (1 - \eta_g)/\eta_g = B \cdot Q_{eg} - N_g\,, \qquad (2)$$

where G_g – mass flow rate of gases, kg/s; Cp_g – isobar heat capacity of gases, KJ/(кg·К); t_{exh} – temperature of gases after gas turbine, °C.

Heat utilization factor of gases, exhausted in GTU (utilization factor)

$$\psi = (t_{eg} - t_{whb})/(t_{fg} - t_1)\,, \qquad (3)$$

where t_{wb} – temperature of gases after waste-heat boiler; t_1 – temperature of external air that, according to international norms, equals 15 °C.

Thermal capacity of waste-heat boiler, MW

$$Q_{whb} = Q_{fg} \cdot \psi = N_g \cdot \psi \cdot (1 - \eta_g) \cdot \eta_g = N_g \cdot \varphi\,, \qquad (4)$$

In order to simplify calculations, values of φ coefficients are shown in Fig. 2.

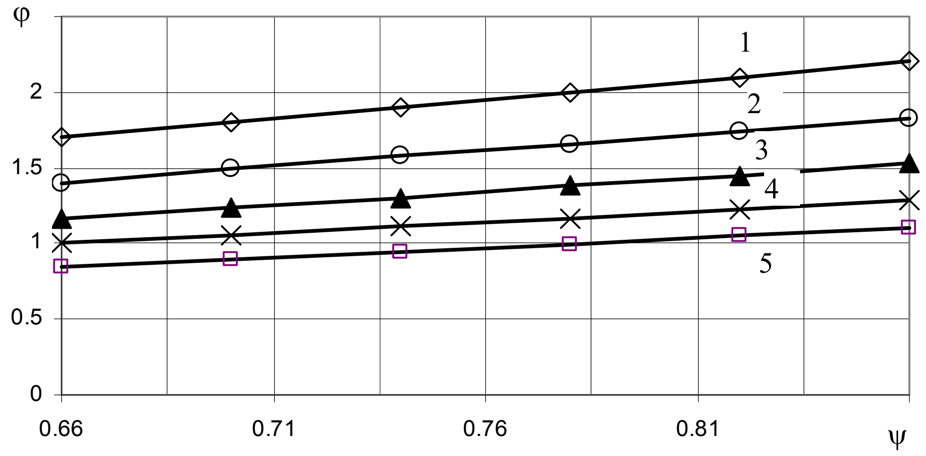

Fig. 2. Values of φ coefficients
1 – η_g = 0.28; 2 – 0.32; 3 – 0.36; 4 – 0.4; 5 – 0.44

For creation of gas steam units on the base of GTU and STU it is necessary that the temperature of gases at the inlet in waste-heat boiler exceeded the temperature of generated steam not less than 100 °C. This condition can be realized by means of additional burning of fuel in BACF. Combustion of additional fuel is carried out in the atmosphere of gases, exhausted in GTU, content of oxygen in these gases, as a rule, is 13 – 16 %. Such method, according to [9] decreases the content of nitrogen oxide in combustion products almost two times.

It is seen from Table 1, that except GTU-16, gas-turbine units of other types can generate in waste-heat boiler the steam with the temperature t_0 = 350 °C without additional burning of fuel. Generation of steam with the temperature t_0 = 450 °C requires additional burning of fuel before waste-heat boiler for all standard sizes of GTU. Besides, for creation of gas-steam units it is necessary that the power of waste-heat boiler equals the power of steam-turbine unit, that consists of the power of STU electric generator N_s and thermal capacity of steam consumers Q_{us}, i. e.

$$Q_{whb} = N_s + Q_{us} = N_s(1+\varepsilon)/\varepsilon = N_s \cdot \beta\,, \qquad (5)$$

where $\varepsilon = N_s/Q_{us}$ – share of electric energy generation on heat consumtion.

First, we determine the indices of GSU without additional burning of fuel. Comparing (4) and (5) we obtain

$$N_s/N_g = N^* = \varphi/\beta\,, \qquad (6)$$

Values of relative power N^* are shown in Fig. 3.

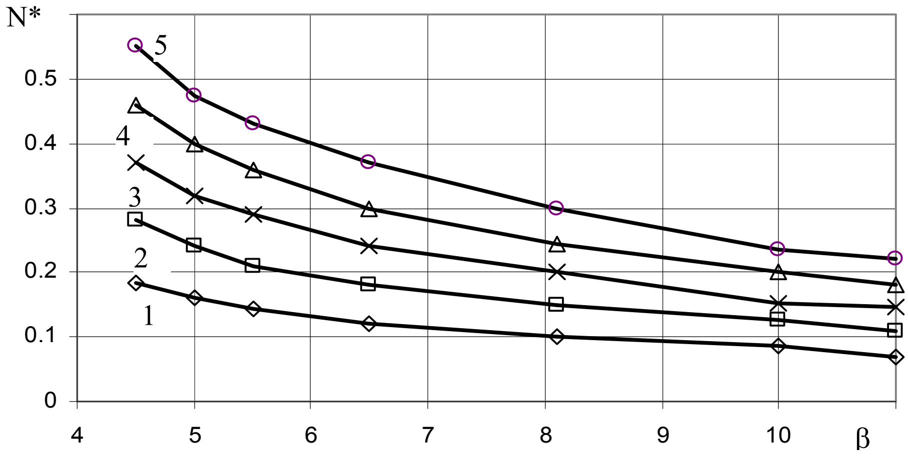

Fig. 3. Values of relative power N^*
1 – φ = 0.8; 2 – 1.2; 3 – 1.6; 4 – 2; 5 – 2/4

Electric power of gas-steam unit will be equal

$$N_{GSU} = N_g + N_s = N_g(1 + \varphi/\beta), \tag{7}$$

Taking into account (6) it is not difficult to determine

$$N^{**} = N_s \,/\, N_{GSU} = \varphi/(\varphi + \beta), \tag{8}$$

$$N^{***} = N_g \,/\, N_{GSU} = \beta/(\varphi + \beta), \tag{9}$$

Hence, for each gas steam unit with certain composition of GTU and STU there exist logical relations between electric powers of separate units.

Useful power of GSU is

$$Q_{GSU} = N_g + Q_{whb} = N_g + N_s + Q_{us} = N_g(1 + \varphi), \tag{10}$$

Proceeding from (1) and (10) specific consumption of equivalent fuel will be equal, kg/GJ

$$b = B \cdot 10^3 / Q_{GSU} = 34.13/\left[\eta_g(1 + \varphi)\right] = 34.13/\gamma, \tag{11}$$

Fig. 4 presents nomograph for determination of specific consumption of equivalent fuel.

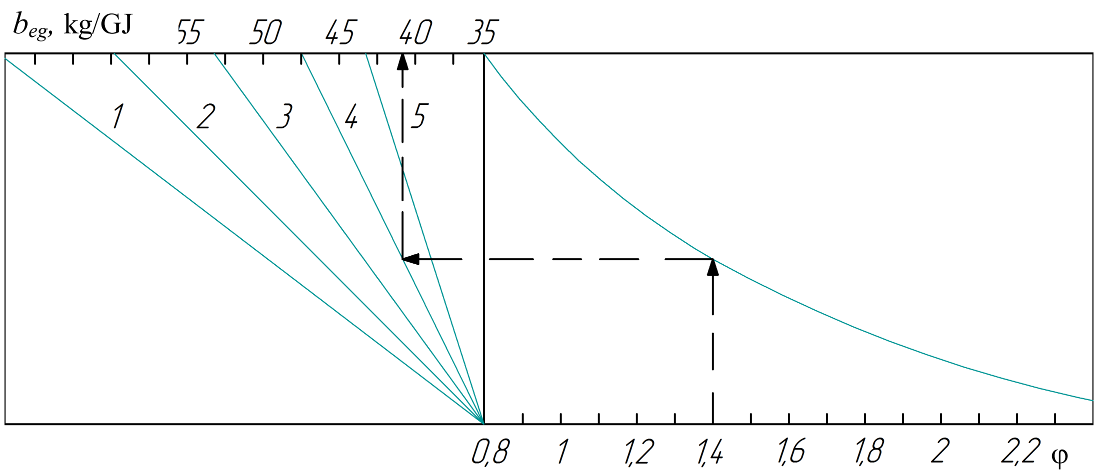

Fig. 4. Nomograpn for determination of specific consumption of equivalent fuel
1 – η_g = 0.28; 2 – 0.32; 3 – 0.36; 4 – 0.4; 5 – 0.44

Coefficient of fuel heat usage, that along with the value of specific consumption of equivalent fuel characterizes the efficiency of energy installations operation and is determined by the formula [10]

$$K = 34.13/b = \eta_g (1+\varphi) = \gamma\,, \tag{12}$$

Thus, the value γ definitely characterizes the efficiency of SGU operation, that increases with the increase of η_g and φ.

Now let us consider the characteristic features of SGU operation with additional burning of fuel. In this case , electric power of GTU, STU and GSU remain invariable and their relations submit to dependences (6), (8) and (9). Additional consumption of equivalent fuel B_{ad} can be determined from the equation of thermal balance of BACF, namely

$$G_g \cdot Cp_g \cdot t_{fg} + B_{ad} \cdot Q_{eg} = (G_g + B_{ad}) \cdot Cp_g \cdot t'_{whb}\,, \tag{13}$$

where the rate of exhaust gases in GTU is determined by (2).

Augend in the left part (13) characterizes the power of exhaust gases in GTU Q_{exh}, and addent – additional power of the burnt fuel, that is spent for heating of gases to the temperature t'_{wb}.

Total consumption of equivalent fuel for GSU is, kg/s

$$B_{GSU} = B + B_{ad} = B(1+\delta)\,, \tag{14}$$

where $\delta = B_{ad}/B$ – share of additional consumption of fuel.

As useful power of GSU does not change, then specific equivalent fuel rate equals, kg/GJ

$$b' = B_{GSU} \cdot 10^3 / Q_{GSU} = 34.13 \cdot (1+\delta)/\gamma = b(1+\delta)\,, \tag{15}$$

The coefficients of fuel heat usage is

$$K' = 34.13/b' = K(1+\delta)\,, \tag{16}$$

It follows, that on condition of constant power of GSU, additional burning of fuel leads to worsening of GSU operation efficiency, namely: specific consumption of equivalent fuel grows and the coefficient of fuel heat usage decreases (1+δ) times.

For example, we compare the operation indices of two GSU of the same power, that operate without additional burning of fuel and with additional burning of fuel. On condition of complete return condensate with the temperature of 103 °C rated capacity of steam consumers from the turbine P-1,5-15/6 is 23.91 MW, and from the turbine P-2,5-35/6 – 22.92 MW. Total capacity of STU will be equal $N_s + Q_{us} = Q_{STU}$ = 23.91+1.5=22.92+2.5=25.42 MW. For creation of GSU on the base of the above-mentioned STU we choose from the Table 1 gas-turbine unit ГТ-20, having the following characteristics: N_g = 20 MW; η_g = 0.365; t_{eg} = 520 °C; B = 1.87 kg/s. Temperature of gases behind the waste-heat boiler is assumed to be equal t''_{wb} =150 °C.

Recovery factor according to (3)

$$\psi = (520 - 150)/(520 - 15) = 0.73267.$$

φ factor according to (4)

$$\varphi = 0.73267 \cdot (1 - 0.365) / 0.365 = 1.2746.$$

Capacity of waste-heat boiler according to (4), MW

$$Q_{whb} = 20 \cdot 1.2746 = 25.49.$$

Since the capacity of waste-heat boiler equals the capacity of STU, there is no need to specify the type of GTU. Capacity of GSU, MW

$$Q_{GSU} = N_g + Q_{SGU} = N_g \cdot (1+\varphi) = 20 \cdot (1+1.2746) = 45.49.$$

γ factor = K according to (11)

$$\gamma = 0.365 \cdot (1 + 1.2746) = 0.83.$$

Specific consumption of equivalent fuel according (11), kg/GJ

$$b = 34.13/\gamma = 34.13/0.83 = 41.12.$$

Creation of GSU on the base of ГТ-20 and steam turbine P-2,5-35/6 requires additional burning of fuel for the increase of gases temperature at the inlet in waste-heat boiler.

Power of exhaust gases in GTU according to (12), MW

$$Q_{fg} = B \cdot Q_{eg} - N_g = 1.87 \cdot 29.3 - 20 = 34.791.$$

Mass flow rate of gases according to (2), kg/s

$$G_g = Q_{fg} \cdot 10^3 /(C(_g \cdot t_{fg}) = 34.791 \cdot 10^3 /(1.1908 \cdot 520) = 56.185.$$

Consumption of additional fuel B_{ad} is determined from the expression (13) on condition, that temperature of gases before waste-heat boiler equals t'_{whb}= 540 °C

$$Q_{fg} + 29300 \cdot B_{ad} = (G_g + B_{ad}) \cdot Cp_g \cdot t'_{whb}$$

$$if\ 34791 + 29300 \cdot B_{ad} = (56.185 + B_{ad}) \cdot 1.196 \cdot 540$$

$$it\ follows\ B_{ad} = 0.0522\ \text{kg/s}.$$

Share of additional consumption of fuel according to (14)

$$\delta = 0.0522 / 1.87 = 0.0279.$$

Value of specific consumption of equivalent fuel according to (15), kg/GJ and coefficient of fuel heat usage according to (16), correspondingly

$$b' = 41.12(1 + 0.0279) = 42.26$$

$$K' = 0.83(1 + 0.0279) = 0.807.$$

Thus, in the given case, the consumption of additional fuel in GSU leads to decrease of operation efficiency by 2.85%.

If electric power of GTU (N_g = 20 MW) was generated at electric stations of energy systems with efficiency factor 0.36, then specific consumption of equivalent fuel would be 94.44 kg/KJ, i. e., two times more than on SGU.

Gas steam units, intended for considerable increase of electric power in the region on the base of the existing industrial thermoelectric plants, operate more efficiently at higher values of efficiency of GTU and exhaust gases temperature. Gas turbine units with greater electric power can function with two or three back-pressure turbines.

Conclusions

1. Simple and convenient for engineering calculations relations are obtained for determination of basic energy operation indices of gas steam units on the basis of industrial thermoelectric plants with back-pressure turbines.
2. High operation efficiency of gas steam units of the given type is revealed.
3. The obtained data is necessary precondition for express – evaluation of efficient operation of gas-steam units while their creation at industrial thermal electric plants.

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