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EFFICIENCY EVALUATION OF ENERGY SUPPLY FROM INDUSTRIAL POWER AND-HEATING PLANTS

Comparative analysis of thermodynamic and economic efficiency of cogenerated (from power and heating plants) and distributive (at electric stations and boiler houses) power supply has been carried out.

Key words: *boiler house, electric station, power and heating plant, equivalent fuel.*

Introduction

The efficiency of energy generation is an important characteristic of fuel operating installations and is determined by fuel consumption. As a result of rise in prices for organic fuel energy saving becomes a problem of paramount importance. Industrial enterprises consume, as a rule, thermal energy (in the form of hot water or steam) and electric energy. The most efficient method of energy saving is cogeneration of electric and thermal energy, that, to greater extent, solves problems, dealing with energy saving, problems, dealing with cogeneration of energy have been solved on legislative level [1].

But, energy supply of large number of industrial enterprises is performed by the so-called distributive scheme, when heat supply is performed from boiler house and electric supply – from electric grid. It is a common knowledge that cogeneration of thermal and electric energy stipulates fuel saving in energy system and reduces technogenic impact on the environment. Regarding the evaluation of energy saving, it should be mentioned that numerous methods have been suggested but none of them is perfect. Greater part of these methods suggest determining the efficiency of power and heating plants by means of efficiency factors of heat and electric energy generation. Analysis of evaluation methods of cogeneration units operation is performed in [2, 3], where the invalidity of such methods due to impossibility of accurate definition of the shares of total fuel consumption, spent for generation of heat and electric energy in the given cogeneration unit, is shown. In [3] it was revealed that the efficiency of cogeneration unit operation depends on two factors: coefficient of electric generation for heat consumption ε and the share of heat output of burnt fuel α_F, spent on heat generation:

$$\varepsilon = \frac{N}{Q}; \ \alpha_F = \frac{Q}{B \cdot Q_l^o}, \tag{1}$$

where N and Q – are electric and heat output of generated electric energy and heat, correspondingly; B – is fuel consumption; Q_l^o – is heat of fuel combustion.

Besides, in [3] it was determined, that the impact of ε and α_F on operation efficiency of cogeneration units of various types has different regularities. Additional complexity is connected with various value of consumed electric energy and heat, consequently, with different consumption of fuel for generation of these kinds of energy. Thus, the correct evaluation of fuel usage efficiency by the kinds of energy, produced at cogeneration units is rather complex. That is why determination of equivalent fuel rate, required for generation of energy and heat, cannot be, as it considered in [4, 5], the basis for tariffs formation for these kinds of energy. Wholesale prices of energy and heat are determined according to market laws and relation between prices for the unit (1 MW/h) of generated energy and heat characterize the value of the above-mentioned kind of energy nowadays.

At power and heating plants of industrial enterprises steam-turbine units of various types are used: counter-pressure turbines of P and ПР types, designed for production of process steam. All the steam, arriving at the turbine is supplied to the consumers. In turbines of П types industrial consumers obtain steam from process extraction. In turbines of T type the steam from extraction heats heating-system water of power and heat supply. Turbines of ПТ type have both industrial and power and heat supply steam extraction. In thermal schemes of steam-turbine units (STU), besides steam-turbine units with counter-pressure turbines, there is a condenser for waste steam condensing. The presence of the condenser, as it is known, reduces thermodynamic efficiency of STU. The experience shows, that units with higher energy efficiency are not always economically more profitable.

Taking into account the above-mentioned, the task to perform comparative analysis of thermodynamic and economic efficiency of cogenerated (at power and heating plants with different STU) and distributive (at condensing electric stations and boiler houses) generation of electric and heat energy was put forward.

Main results

Using the term thermodynamic efficiency we mean equivalent fuel rate for generation of the unit energy, namely, on generation, but not supply. Supplied energy depends on the perfection degree of energy equipment operation, quality of automatic regulation of basic and auxiliary equipment, state of transport networks, etc. For industrial enterprises energy supply from power and heating plants has advantages as compared with distributive scheme of supply, since generation of heat and electric energy is performed on the site of consumption and does not result in considerable losses in transporting networks.

For comparative analysis of energy supply efficiency by distributive and cogeneration schemes all types of steam turbine units (STU), applied at industrial power and heating plants of small capacity are taken. Main characteristics of STU from [6] are reduced in Table 1.

Table 1

Characteristics of steam turbine units

Indexes	Steam turbine units					
	Р-6-35/5	ПР-6-35(10)5	П-6-35/5	Р-12-35/5	Т-12-35	ПТ-12-35/10
Steam temperature be yond the turbine, °C	225	225	29	225	29	29
Steam temperature at industrial extraction, °C	-	300	-	-	-	300
Steam temperature at power and heat supply, °C	-	-	-	-	105	105
Steam rate per turbine, t/h	60	80.5	55.8	114.7	90	119
Steam rate in industrial extraction, t/h	-	30.5	-	-	-	50
Steam rate in power and heat supply, t/h	-	-	-	-	65	40
Steam rate in condenser, t/h	-	-	15.8	-	16.5	29

All STU, presented in Table 1 have the same original parameters of the steam (pressure 3,5 MPa and temperature 435 °C) and the same temperature of feed water, that equals 150 °C. Enthalpy of steam, condensates of steam and water were determined from Tables [8]. Efficiency factors of industrial steam generators at power and heating plants and boilers of the system of distributive energy supply have been chosen to be identical, values of which is 0.9. It is quite clear, that comparison of indices of cogeneration (at power and heating plants) and distributive operation (at condensing power plants and boiler houses) was performed on condition of equal values of electric N and heat Q capacities. Average efficiency factor of condensing power plants in energy system was 0.35, and efficiency factor of electric grids – 0.9.

Aggregate capacity, generated by STU, is determined by the formula, MW:

$$Q=\sum_{i=1}^{n} D_i\left(h_i-h_i'\right)\cdot 10^{-3}, \tag{2}$$

where D_i – is steam rate in the given extraction, kg/s; h_i and h_i' – is enthalpy of extracted steam and condensate of this steam, correspondingly.

Coefficient ε, characterizing generation of energy for heat supply, is determined by the formula (1).

Steam generator capacity for power and heating plants is calculated by the known formula, MW:

$$Q_{SG}=D_0\left[\left(h_0-h'_{fw}\right)+\alpha_{bw}\left(h'_{bw}-h'_{fw}\right)\right]\cdot 10^{-3}, \tag{3}$$

where D_0 – is steam rate per STU, kg/s; α_{bw} – is share of blow -down water; h_0 – is enthalpy of steam behind steam generator, correspondingly; h'_{fw}, h'_{bw} – is enthalpy of feed water and blow-down water, correspondingly

Equivalent fuel rate, burnt in the furnace of steam generator, kg/s:

$$B_e = \frac{Q_{SG}}{\left(Q_e \cdot \eta_{SG}\right)}, \tag{4}$$

where $Q_e = 29.3$ MJ/kg – is heat of combustion of equivalent fuel; η_{SG} – is efficiency factor of steam generator.

The share of fuel thermal capacity α_F, spent for generation of heat, is determined by (1).

The coefficient of fuel heat consumption:

$$K_{FHC} = \left(N + Q\right)/\left(B_e Q_e\right). \tag{5}$$

Equivalent fuel rate for generation of unit of energy by [3], kg/GJ:

$$\text{в}_e^{PHP} = 34.143 / K_{FHC}. \tag{6}$$

If energy supply is performed using the distributive scheme equivalent fuel rate at condensing power plants (CPP) B_{CPP}, in boiler houses B_B and total consumption B_T are, kg/s:

$$B_{CPP} = \frac{N}{Q_l \cdot \eta_{CPP} \cdot \eta_{eg}};\ B_F = \frac{Q_{SG}}{\left(Q_e \cdot \eta_F\right)};\ B_T = B_{CPP} + B_F, \tag{7}$$

where η_{CPP} and η_{eg} – efficiency factor of CPP and electric grids, correspondingly; η_F– is efficiency factor of the boiler.

Equivalent fuel rate per unit, kg/GJ:

$$\text{в}_e^{O} = \frac{B_T \cdot 10^3}{(N + Q)}. \tag{8}$$

Saving of equivalent fuel at power and heating plants as compared with distributive energy supply system, t/h:

$$\Delta B = 3.6(B_T - B_e). \tag{9}$$

Amount of equivalent fuel saving characterizes the advantage of cogeneration scheme of energy supply as compared with distributive scheme, both from energy aspect and ecological aspect. We consider the comparative characteristic of thermodynamic efficiency to be the relation of fuel heat usage coefficients, i. e.:

$$K_{TE} = K_{FHU}^{PHP} / K_{FHU}^{D}, \tag{10}$$

where K_{FHU}^{PHP} and K_{FHU}^{S} – is fuel heat usage coefficient at power and heating plant and in distributive scheme of energy supply, correspondingly.

Coefficient K_{TE} shows how many times the efficiency of fuel usage in cogeneration scheme of energy supply is higher than in distributive scheme. If $K_{TE} > 1$, then cogeneration scheme is expedient, if $K_{TE} < 1$, then, vice versa. Calculated indexes of energy systems operation on condition of identical heat and electric power are shown in Table 2.

Table 2

Main indexes of energy supply systems operation

Indexes	Type of steam turbine unit					
	Р-6-35/5	ПР-6-35(10)5	П-6-35/5	Р-12-35/5	Т-12-35	ПТ-12-35/10
	Cogeneration system					
Heat capacity of steam generators, MW	44.559	57.336	41.431	85.162	66.825	88.342
Equivalent fuel rate, kg/s	1.690	2.174	1.571	3.230	2.534	3.350
Generated heat capacity, MW	38.512	51.336	29.702	75.596	41.172	63.526
Coefficient of electric energy generation on heat demand	0.156	0.117	0.202	0.159	0.291	0.189
Share of fuel capacity for heat generation	0.778	0.806	0.645	0.799	0.555	0.647

Coefficient of fuel heat usage	0.899	0.900	0.776	0.926	0.716	0.769
Specific fuel rate, kg/GJ	38.0	37.9	44.0	36.9	47.7	44.4
Distributive scheme						
Equivalent fuel rate for electric energy generation, kg/s	0.650	0.650	0.650	1.300	1.300	1.300
Equivalent fuel rate for heat generation	1.460	1.947	1.126	2.867	1.561	2.409
Equivalent fuel total rate, kg/s	2.111	2.597	1.776	4.167	2.861	3.709
Coefficient of fuel heat usage	0.72	0.75	0.69	0.72	0.63	0.69
Specific fuel rate, kg/GJ	47.43	45.31	49.78	47.59	53.84	49.13
Comparative indexes						
Saving of equivalent fuel at PHP, t/h	1.515	1.521	0.739	3.375	1.179	1.293
Index of thermodynamic efficiency	1.249	1.194	1.131	1.290	1.129	1.107

It is seen from Table 2, that thermodynamic efficiency of all steam turbine units, operating on cogeneration scheme of energy supply is higher than the efficiency of energy supply, using the distributive scheme. Most efficiently (20 – 29 %) STU with back-pressure turbines operate. More efficient operation of cogeneration units provides corresponding saving of fuel and reduces technogenic impact on the environment. As a rule, electric, power and heat generation capacity of industrial enterprises is far less than constant industrial thermal capacity. That is why, turbines with back-pressure must be predominant in the structure of industrial power and heating plants. It is explained not only by their efficient operation, but also by the absence of cumbersome system of technical water supply and expenses for its maintenance.

Unlike industrial, the plants designed for power and heating supply (heating hot water supply) have variable, depending on the season of the year, capacity. Their loading in heating period is 70 – 80 % higher than in non-heating period. That is why, the operation of extraction turbines in non-heating period will tend to the operation in condensation mode. In this case, generation of electric energy in such turbines can be inferior to the efficiency of energy generation by powerful condensing power plants, operating at higher initial parameters of steam, hence, with higher efficiency factors. As a result, the efficiency of energy generation at such turbines in non-heating period can be even lower than in case of energy supply, using the distributive scheme. That is why, it is recommended to equip power and heating plants with two back-pressure turbines to cover heat loadings in heating and non-heating periods [9].

We will evaluate the economic efficiency of the above-mentioned systems of energy supply. Let us assume, that the length and quality of heating networks from power and heating plant and boiler houses are identical, and heat losses in them are 13%. Losses in electric grid from power and heating plant are considered to be 5%, energy consumption for auxiliary power is also 5%. Losses of energy in the networks of power system for distributive scheme of energy supply have already been taken into account. We will assume, that the index of economic efficiency of energy supply is the ratio of revenue for supplied kinds of energy to charges for fuel.

Charges for fuel, Hrs:

$$Z_f = Ц_f \cdot B \cdot 3.6 \cdot \tau \,, \tag{11}$$

where $Ц_f$ – is the price of fuel, Hrs/t; B – fuel rate, kg/s; τ – certain period of operation, h.

Revenue for heat, Hrs:

$$V_H = Ц_H \cdot Q \cdot (1 - \Delta q) \cdot \tau \,, \tag{12}$$

where $Ц_H$ – is price of supplied heat, Hrs/(MW·h); Δq – is the share of heat losses in the system.

Revenue for electric energy, Hrs:

at PHP

$$V_E = Ц_E \cdot N \cdot (1 - \Delta e_{los} - \Delta e_{ap}) \cdot \tau \,; \tag{13}$$

for distributive scheme

$$V_E = Ц_E \cdot N \cdot \tau \,, \tag{14}$$

where $Ц_E$ – is the price of electric energy, Hrs/(MW/h); Δe_{los} – is the share of losses in electric grids; Δe_{ap}

– is the share of auxiliary power.

Index of economic efficiency:

$$\eta_e = (V_H + V_E)/Z_f. \tag{15}$$

As an example we will determine the index of economic efficiency of energy supply from PHP, equiped with a turbine P-6-35/5 (see Table 2) and index of economic efficiency of energy supply by distributive scheme for identical capacities $N = 6$ MW, $Q = 38.512$ MW. We will assume that fuel price $Ц_F = 3000$ Hrs per ton; $Ц_t = 500$ Hrs per MW h; $Ц_e = 1000$ Hrs per MW h; $\tau = 1$ hour. The results of comparative calculations are shown in Table 3.

Table 3

Comparative indexes of economic efficiency of energy supply

Indexes	Scheme of energy supply	
	THP	Distributive
Fuel expenses, Hrs	18249	22794
Revenue for heat, Hrs	16752.7	16752.7
Revenue for electric energy, Hrs	5400	6000
Total revenue for sources of power, Hrs	22152.7	22752.7
Index of economic efficiency	1.214	0.9982

It is seen from Table 3, that the index of economic efficiency of energy supply from PHP exceeds the value of this index in case of energy supply, using the distributive scheme. Relative index of economic efficiency of energy supply equals: $\eta_{er} = \eta_e^{PHP} / \eta_e^d = 1.214/0.9982 = 1.216$. For the same variant in Table 2, the value of relative index of thermodynamic efficiency is 1.216. It should also be noted, that fuel price exercises greatest impact on economic efficiency of energy supply, its increase rate, as a rule, outstrips the growth of cost for heat and electric energy. It is obvious, that the reduction of heat and electric energy losses is important factor, influencing the increase of economic efficiency of energy supply.

Conclusions

1. Thermodynamic and economic efficiency in case of combined generation and supply of energy at industrial THP of any structure is always higher than for distributive scheme of energy supply.
2. Thermodynamic efficiency of energy supply always exceeds economic efficiency.
3. Fuel price exercises the greatest impact on economic efficiency.

REFERENCES

1. Закон України про комбіноване виробництво теплової та електричної енергії (когенерацію) та використання складного потенціалу // Відомості Верховної Ради, 2005. – № 20. – С. 278 – 285.

2. Чепурний М. М. Ефективність роботи паротурбінних і газотурбінних теплоелектроцентралей / М. М. Чепурний // Вісник Вінницького політехнічного інституту. – 2008. – № 2. – С. 36 – 40.

3. Показники ефективності роботи енергетичних установок для сумісного виробництва теплової та електричної енергії [Електронний ресурс] / М. М. Чепурний, С. Й. Ткаченко, Н. В. Пішеніна // Наукові праці Вінницького національного технічного університету. – № 1. – 2010. Режим доступу до журн.: http://www.nbuv.gov.ua/e-journals/VNTU/2010_1/2010-1.files/uk/10mmcaee_ua.pdf.

4. ГДК 34.09.108.98. Розподіл витрат палива на відпущену електричну і теплову енергію при їх комбінованому виробництві: Методика НДІ Енергетики. – Київ, 1998. – 22 с.

5. Вінницький І. П. Спрощений метод визначення витрат палива на відпущену електричну і теплову енергію за їх комбінованого виробництва на теплових електростанціях / І. П. Вінницький, С. М. Герасимов, П. О. Гут // Энергетика и электрификация. – 2004. – № 8. – С. 42 – 45.

6. Теплотехнический справочник / [под ред. В. Н. Юренева и П. Д. Лебедева]. – М.: Энергия, 1975. – т. 1. – 744 с.

7. Чепурний М. М. Енергозбережні технології в теплоенергетиці / М. М. Чепурний, С. Й. Ткаченко. – Вінниця: ВНТУ, 2009. – 114 с.

8. Ривкин С. А. Термодинамические свойства воды и водяного пара / С. А. Ривкин, А. А. Александров. – М.: Энергоатомиздат, 1980. – 142 с.

9. Чепурний М. М. Сучасні проблеми теплофікації / М. М. Чепурний, Н. В. Пішеніна, О. В. Куцак // Вісник Вінни-

цького політехнічного інституту. – 2010. – № 5. – С. 68 – 71.

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