Fundamentals of the procedure of a comparative analysis of the thermodynamic effectiveness for power generation facilities in a multigeneration complex with various combinations of their main equipment items

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Abstract. A problem is examined of improving the efficiency of power generation facilities during their operation in a multi-generation complex. The efficiency of operation is raised by proper distribution of additional power and heat generating capacities used to cover the consumers’ demand for additional (except for electricity and heat) utilities, among various main equipment items of generation facilities. In this case, electricity and heat generated with a higher efficiency is delivered to the consumers, and electricity and heat with no demand, which have also been generated with a higher efficiency, are utilized at the generation facility to produce other utilities (for example, hydrogen, compressed air, cold, etc.) that are centrally delivered to industrial and social facilities.

1. Introduction

A new line for improving the efficiency of energy generation with application of so-called multigeneration complexes (MC) has been dynamically developing in recent years [1 – 7]. A multigeneration complex comprises energy generation facilities and energy consumption facilities. The former basically includes either condensation (type K) or cogeneration (type T or PT) turbines. Generation facilities are basically intended for generation of the two main kinds of utilities which are either only electricity or electricity and heat. Consumption facilities of MC can be various industrial enterprises or social / municipal facilities. Generating facilities of MC offer combined generation of various utilities, a list of which can include, in addition to electricity or electricity and heat, cold, compressed air, liquefied natural gas, etc. All generated utilities are delivered in a centralized manner to consumers. Methodological issues of determining the thermodynamic efficiency of multi-generation technology for the overall energy supply system as combined generation of various kinds of energy carriers in comparison with their separate generation were examined in [6]. In this case, the exergetic efficiency was selected as an efficiency criterion. This has yielded a formula for assessment a change in the exergetic efficiency on a change-over for the separate to combined generation. Recommended practices for assessing MCs on the basis of both thermodynamic and economic criteria are outlined in [7].
2. Formulation of the problem
This report deals with a different formulation of the problem. The efficiency of application of the multi-generation technology is determined only for generating facilities included in an MC. With this formulation, the problem is first solved of converting the main equipment of the generation facilities to efficient modes of operation close the optimal modes for generation of electricity and heat considering seasonal or daily variations in their demand. The demanded electricity and heat produced with a higher efficiency than it would be under improper conditions, are delivered to external consumers, while the rest of electricity and heat with no demand is used to produce other utilities (for example, hydrogen, compressed air, cold, etc.) in the equipment intended for this.

The efficiency of generating facilities included in an MC can be improved by proper distribution of additionally generated electricity and heat used to produce additional utilities (except for electricity and heat) demanded by consumers, among the main equipment items of the generating facilities.

With this formulation, we should answer two questions:
1. What are the capabilities to generate various, consumer-demanded utilities at generation facilities included in a multi-generation complex?
2. How can the main equipment of generation facilities be used with a maximum efficiency to produce utilities in addition to electricity and heat during periods of the reduced demand for electricity or heat using spare power and heat generation capacities?

An answer to the first question can be offered by an analysis of the types of the main equipment used to generate power or heat and of the standard modes of operation of this equipment. An answer to the second question can be obtained in analyzing the standard performance of the main equipment of generation facilities (or one facility).

To explain the above-mentioned, let us consider the following example. A thermal power plant of the “large” power industry has two power units: one with a 300 MW K-300-240 condensing steam turbine and one with a 200 MW K-200-130 condensing steam turbine. The consumer demands for a utility whose generation requires 100 MW of electricity. Under these conditions during the considered period, the power unit with the K-300-240 turbine operates with an output of 200 MWel, and the power units with the K-200-130 turbine, with an output of 100 MWel. At which power unit it would be more efficient to increase generation of electric power generation by changing over the equipment to operation under rated conditions?

To answer this question, we have to find out the effect of two factors. Thus, on the one hand, the heat rate at the K-300-240 power unit is less than that at the K-200-130 power unit. Hence, less fuel will be required to generate additional 100 MWel. of power at the K-300-240 power unit than at the K-200-130 power unit. However, on the other hand, the K-200-130 power unit features much greater deviations from rated conditions than the K-300-240 power unit does. Therefore, in generating 200 MWel., the fuel saving determined by a decrease in the heat rate due to changing over the K-200-130 to operation under rated conditions may be greater for this power unit than that for the K-300-240 power unit.

In this example, making a final decision requires calculations based on the heat rated vs. power output dependences for the K-300-240 and the K-200-130 power unit derived from the standard specifications for the equipment [8, 9].

3. Substantiation of the selection of a criterion for evaluation of the thermodynamic efficiency of generation facilities included in a multigenerating complex at various combinations of main equipment items in the generation facilities
With the problem formulation adopted in this report, the main problem to be solved is to select equipment that will offer a maximum efficiency in the production of additional utilities demanded by the consumer. Here, for a thermodynamic criterion for assessing the efficiency of a generating facility (or several generating facilities) with different types of equipment, as distinguished from the problem studied in [6], an energy criterion should be used. This criterion is the consumption of
the primary energy carrier for the production of electricity, heat, and additional utilities comparing the total costs of primary energy for their production on case-by-case basis. Therefore, in this case, the efficiency assessment criterion will be the total fuel consumption for generation of the required amount of electricity, or electricity and heat, as well as all additional products, whether they are utilities (for example, hydrogen, liquefied gas, etc.) or not (for example chemical fertilizers, etc.) for each of the compared types of the main equipment items at a generation facility.

4. Development of a procedure for assessment the efficiency for generation facilities with various types of the main equipment

The initial conditions for the problem to be solved are as follows:

1) A generation facility integrated into a multi-generation complex has two steam-turbine units (STU) of different types and power, as well as other equipment for production of additional utilities, which can be driven with both electric power and heat.

2) Both STUs operate away from the best efficiency point, with reduced electric and heat output due to reduced demand for them thereby increasing the heat rate as compared to that in operation under the optimal conditions.

3) A potential is brought about for generating additional utilities demanded by consumers by increasing the electric and thermal power of the main equipment by $\Delta N$ and $\Delta Q$, respectively, which enables us to improve the efficiency of the power units due to their operation under conditions which are optimal or close to optimal.

In the most general form, when all available spare capacities are used to produce electricity and heat as applicable, the total fuel consumption $B_\Sigma$ can be evaluated by the expression:

$$B_\Sigma = b_{113} (N_{10} + \Delta N_1) + b_{11T} (Q_{10} + \Delta Q_1) + b_{213} (N_{20} + \Delta N_2) + b_{21T} (Q_{20} + \Delta Q_2) \quad (1)$$

Here, $b_{113}, b_{213}$ are the fuel rates for electricity generation at power units no. 1 and 2, respectively; $b_{11T}, b_{21T}$ are the fuel rate for heat generation at power unit no. 1 and 2, respectively; $N_{10}, N_{20}$ are the electric power of power units no.1 and 2, respectively, under the initial operating conditions; $\Delta N_1, \Delta N_2$ are an increase in the electric output of power units no. 1 and 2, respectively; $Q_{10}, Q_{20}$ are the heat outputs of power units no. 1 and 2, respectively, under the initial operating conditions; $\Delta Q_1, \Delta Q_2$ are an increase in the heat output of power unit no. 1 and 2, respectively.

Expression (1) makes it possible to calculate the total fuel consumption for various special cases:

1) Two condensing turbines with loading either of them. The terms describing heat generation in expression (1) are excluded. If we assign no. 1 to the pump unit carrying additional load, then

$$B_\Sigma = b_{113} (N_{10} + \Delta N) + b_{20} N_{20} \quad (2)$$

2) Two cogeneration turbines, one of them (with no. 1) carries only the heat load $\Delta Q$.

$$B_\Sigma = b_{113} N_{10} + b_{11T} (Q + \Delta Q) + b_{203} N_{20} + b_{20T} Q_{20} \quad (3)$$

where $b_{203}, b_{20T}$ are the fuel rates for production of electricity and heat, respectively, at the power unit no. 2 under the initial operating conditions.

3) Condensing (1) and cogeneration (2) turbines; the first carries an additional electrical load of $\Delta N$, the second carries an additional heat load of $\Delta Q$.

$$B_\Sigma = b_{113} (N_{10} + \Delta N) + b_{203} N_{20} + b_{21T} (Q + \Delta Q) \quad (4)$$

5. Examples of calculations

Two Condensing Type Power Units Comparison is made for two types of equipment: a power unit with a K-200-130 turbine and a power unit with a K-300-240 turbine, and for two options for distribution of an additional electric power of $\Delta N = 20$ MWel. In option 1, additional 20 MWel. is produced by the K-200-130 power unit while the K-300-240 power unit carries an initial load of
280 MW. In option 2, the additional power is generated by the K-300-240 power unit while the K-200-130 power carries a constant load of 180 MW.

Conditions Assumed in the Calculations

K-200-130 power unit:
1) The K-200-130 power unit carries a load of 180 MW with a fuel rate of 0.3143 kg c.e./kW h and a fuel consumption of 56.58 t.c.e./h.
2) The unit output rises to 200 MW that reduces the fuel rate to 0.3127 kg c.e./kW h.

K-300-240 power unit
1) The K-300-240 power unit carries a load of 280 MW with a fuel rate of 0.3019 kg c.e./kW-h and a fuel consumption of 84.53 t.c.e./h.
2) The unit output rises to 300 MW that reduces the fuel rate to 0.3002 kg c.e./kW h.

To avoid confusion, the K-200-130 power unit will be power unit no.1, and the K-300-240 power unit will be power unit no. 2.

In accordance with the adopted assumptions, the efficiency values of the power units with condensing STUs are compared by the values of \( \Sigma V \) calculated by formula (2) using the outputs and the fuel rate values for these power units given in Table 1.

Results of Calculations

Option 1:
\[
B_{\Sigma 1} = b_{113} (N_{10} + \Delta N) + b_{20} N_{20} = 0.3127 (180000 + 20000) + 0.3019 \cdot 280000 = 147072 \text{ kg c.e./h.} \tag{5}
\]

Option 2:
\[
B_{\Sigma 2} = b_{113} (N_{10} + \Delta N) + b_{20} N_{20} = 0.3143 \cdot 180000 + 0.3002(280000 + 20000) = 146634 \text{ kg c.e./h} \tag{6}
\]

Thus, with the adopted assumptions, Option 2 offering a total coal equivalent consumption of equal to \( B_{\Sigma 2} = 146.634 \text{ t.c.e./h} \) is thermodynamically more efficient than Option 1 with a total equivalent coal consumption of \( B_{\Sigma 1} = 147.072 \text{ t.c.e./h} \) does.

Two Cogeneration Type T-50-130 and T-100-130 STUs

Conditions Assumed in the Calculations

1) The T-50-130 STU operates with an electric power of \( N_{OT50} = 30 \text{ MW} \) and a heat output of \( Q_{OT50} = 40 \text{ Gcal/h} \).
2) The T-100-130 STU operates with an electric power of \( N_{OT100} = 80 \text{ MW} \) and a heat output of \( Q_{OT100} = 110 \text{ Gcal/h} \).
3) Option 1. Additional 10 Gcal/h is generated by the T-50-130 STU operating a constant electric power of 30 MW with no change in the operating conditions of the T-100-130 STU.
4) Option 2. Additional 10 Gcal/h is generated by the T-100-130 STU operating at a constant electric power of 80 MW with no change in the operating conditions of the T-50-130 STU.

Calculations for power units with cogeneration STUs to be performed in accordance with their standard specifications and the proposed procedure for determining the thermodynamic efficiency, require preliminary calculation of the specific characteristics at the initial loads of the power units.

**Table 1. Initial data for calculations for K-200-130 and K-300-240 STUs**

| Characteristic          | Option 1 | Option 2 |
|------------------------|----------|----------|
| STU                    | K-200    | K-300    | K-200    | K-300    |
| Initial power, \( N_0 \), MW | 180      | 280      | 180      | 280      |
| Final power, \( N_{KOH} \), MW | 200      | 280      | 180      | 300      |
| Fuel rate *, \( b_0 \), kg c.e./kW·h | 0.3143   | 0.3019   | 0.3143   | 0.3019   |
| Final heat rate*, \( b_1 \), kg c.e./kW·h | 0.3127   | 0.3019   | 0.3143   | 0.3002   |

* According to [8] and [9].
Calculation of specific characteristics at the initial loads of the pump units

In accordance with the standard specification of the T-50-130 STU [10], the heat rate \( q_{0T50} \) is 1810 kcal/kW h at an electric power of \( N_{0T50} = 30 \) MW and a heat output of \( Q_{0T50} = 40 \) Gcal/h.

For the boiler unit efficiency assumed to be \( \eta_{KA} = 0.9 \) in the calculations, the heat rate \( q_{0KAT50} \) for the boiler unit in this case is

\[
q_{0KAT50} = q_{0T50} / \eta_{KA} = 1810 / 0.9 = 2011 \text{ kcal/kW·h.}
\]

In this case, the rate of coal equivalent (LHV is \( Q_{n} = 7000 \) kcal/kg) will be

\[
b_{30T50} = q_{0KAT50} / Q_{n} = 2011 / 7000 = 0.287 \text{ kg c.e./kW·h,}
\]

at a fuel rate of

\[
B_{30T50} = b_{30T50} \cdot N_{0T50} = 0.287 \cdot 30000 = 8619 \text{ kg c.e./h} = 8.619 \text{ t.c.e./h.}
\]

The heat absorbed in the boiler unit to generate the heat output \( Q_{0KAT} \) can be calculated by the expression

\[
Q_{0KAT} = Q_{0T50} / \eta_{KA} = 46.52 / 0.9 = 51.69 \text{ MW.}
\]

In this case, the fuel rate \( B_{TOT50} \) for heat production will be

\[
B_{TOT50} = B_{30T50} + B_{0T50} = 14.968 \text{ t.c.e./h.}
\]

The T-100-130 STU operates with an electric power of \( N_{0T100} = 80 \) MW and a heat output of \( Q_{0T100} = 110 \) Gcal/h (127.93 MW). In accordance with the standard specification of T-100-130 STU [11], the heat rate \( q_{0T100} \) is 1425 kcal/kW·h.

With the boiler unit efficiency assumed to be \( \eta_{KA} = 0.9 \), the heat input \( Q_{0KAT100} \) in the boiler unit in this case is

\[
q_{0KAT100} = q_{0T100} / \eta_{KA} = 1425 / 0.9 = 1583 \text{ kcal/kW·h.}
\]

The rate of coal equivalent (with a lower heating value of \( Q_{n} = 7000 \) kcal/kg c.e.) for generation of electricity is

\[
b_{30T100} = q_{0KAT100} / Q_{n} = 1583 / 7000 = 0.226 \text{ kg c.e./kW·h,}
\]

and the fuel flow for electricity generation is

\[
B_{30T100} = b_{30T100} \cdot N_{0T100} = 0.226 \cdot 80000 = 18095 \text{ kg c.e./h} = 18.095 \text{ t.c.e./h.}
\]

The heat input in the boiler unit required to produce the heat output \( Q_{0KAT100} \) can be calculated by the expression:

\[
Q_{0KAT100} = Q_{0T100} / \eta_{KA} = 127.93 / 0.9 = 142.14 \text{ MW.}
\]

The coal equivalent consumption \( B_{TOT50} \) for heat generation will be

\[
B_{TOT50} = Q_{0KAT100} / Q_{n} = 142.14 / 7000 = 0.020 \text{ kg c.e./kW·h,}
\]

\[
= 4.850 \text{ kg c.e./h} = 17.460 \text{ t.c.e./h.}
\]
Thus, under the specified initial conditions, the total fuel consumption in the T-100-130 STU is
\[ B_{\Sigma 100} = B_{30T100} + B_{50T100} = 18.095 + 17.460 = 35.555 \text{ t.c.e./h.} \] (18)

The fuel rate for heat generation under these conditions is
\[ b_{\text{T100}} = \frac{B_{\text{T100}}}{Q_{\text{T100}}} = \frac{17460}{127930} = 0.136 \text{ kg c.e./kW·h.} \] (19)

Estimation for various options for the generation of additional heat

In accordance with the assumption and conditions adopted for the calculations, the efficiency values of the power units with a cogeneration STU are compared by the total fuel consumption \( B_{\Sigma} \) calculated by formula (3) where are used the values of the power units power and the fuel rate for generation of electricity given in Table 2.

**Table 2. Initial data for the calculation of a facility consisting of a T-50-130 STU and a T-100-130 STU**

| Characteristic                              | Option 1 | Option 2 |
|---------------------------------------------|----------|----------|
| STU                                         | T-50     | T-100    | T-50     | T-100    |
| Initial electric power \( N_0 \), MWel.     | 30       | 80       | 30       | 80       |
| Final electric power \( N_{\text{KOH}} \), MWel. | 30       | 80       | 30       | 80       |
| Initial heat output \( Q_0 \), MW           | 46.52    | 127.93   | 46.52    | 127.93   |
| Final heat output \( Q_{\text{KOH}} \), MW | 58.15    | 127.93   | 46.52    | 139.56   |
| Heat output change \( \Delta Q \), MW       | 11.63    | 0        | 0        | 11.63    |
| Initial fuel rate for electricity generation **, \( b_0 \), kg c.e./kW·h | 0.287   | 0.226    | 0.287    | 0.226    |
| Final fuel rate for electricity generation **, \( b_1 \), kg c.e./kW·h | 0.260   | 0.226    | 0.287    | 0.213    |
| Final fuel rate for heat generation **, \( b_1 \), kg c.e./kW·h | 0.136   | 0.136    | 0.136    | 0.136    |

**According to [10] and [11] for a boiler efficiency of 0.9.**

Option 1

The total fuel consumption by the two power units in Option 1 is calculated by the expression
\[ B_{\Sigma 1} = b_{103\text{N}10} + b_{11T} (Q_{11T} + Q_{\text{DOB}}) + b_{203} N_{20} + b_{20T} Q_{20T} = 0.260 \times 30000 + 0.136 (46520 + 11630) + 0.226 \times 80000 + 0.136 \times 127930 = 51186 \text{ kg c.e./h.} \] (20)

Option 2

The total fuel consumption by the two power units in Option 2 is calculated by the expression
\[ B_{\Sigma 2} = b_{103\text{N}10} + b_{10T} Q_{10T} + b_{223} N_{20} + b_{22T} (Q_{22T} + Q_{\text{DOB}}) = 0.287 \times 30000 + 0.136 \times 46520 + 0.213 \times 80000 + 0.136 (127930 + 11630) = 50957 \text{ kg c.e./h.} \] (21)

Thus, for the adopted calculation conditions, Option 2 with a total coal equivalent rate of \( B_{\Sigma 2} = 50.957 \) t.c.e./h turns out to have a higher thermodynamic efficiency than that of Option 1 with a total coal equivalent rate of \( B_{\Sigma 2} = 50.957 \) t.c.e./h.

6. Conclusions

1. The basic principles are proposed of a procedure for analyzing the thermodynamic efficiency of generating facilities with various combinations of their main equipment items and included in a multi-generating complex.
2. Examples are given of the calculation under the operating conditions typical for Russia of the thermodynamic efficiency for generation facilities having various combinations of their main equipment and included in a multi-generation complex.

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