Comparison of separate and combined generation of energy carriers at a condensing power plant

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Abstract. Generation of additional produced energy carriers at the station, such as heat, cold, compressed air, hydrogen, air separation products, etc., due to the use of electric power unclaimed by consumers during off-peak electric load periods lets keeping the lower specific fuel consumption for the generation of electricity. The article is devoted to comparison of efficiency of two ways of power supply of the consumer with the electric power and one other produced energy carrier: separate and combined generation.

1. Introduction
As is known, the thermodynamic efficiency of steam turbine plants depends on how close the generated electric power to its rated value. The more power generated at a certain time differs from the rated power, the worse the performance (for example, the specific fuel consumption for power generation) both of the turbo unit and, consequently, of the entire power unit [1].

The power plants operating in the peak of the load curve are often forced to work with lower capacities in comparison with the rated values because of existing seasonal and daily off-peak of the electric load. In this regard, one of the possible ways to increase the efficiency of the condensing power plant is to ensure its operation in modes close to nominal. The electric load leveling, and hence the maintaining optimum operation mode of condensing power plant, is possible in the case of additional produced energy carriers generation at the station, such as heat, cold, compressed air, hydrogen, air separation products, etc., due to the use of electric power unclaimed by consumers during off-peak electric load periods [2]. For this purpose the condensing power plant should be equipped with appropriate devices and aggregages for generation of these energy carriers.

2. Comparison of separate and combined generation energy carriers at the condensing power plant
Generation of electricity and other produced energy carriers at the condensing power plant can be considered as their combined generation and represents an alternative way to their existing separate generation.

The article is devoted to comparison of efficiency of two ways of the consumer power supply with electricity and one other produced energy carrier. The first variant of power supply is the separate generation of electricity at the condensing power plant and an additional produced energy carrier at a special installation operating from a common network, figure 1. The second variant of power supply is the combined generation of electricity and produced energy carrier at the condensing power plant, figure 2.
STP – steam turbine plant; PPEC – plant for generation of produced energy carrier; \(B_{feSTPc}\) – fuel consumption per unit of time for generation of electricity at STP with separate generation; \(N_{es}\) – electric power transmitted to the consumer at separate generation of electric power and produced energy carrier; \(B_{fePEC}\) – fuel consumption per unit time for the generation of electricity used to drive the plant of the produced energy carrier at separate generation; \(B_{mPEC}\) – material consumption for plant of the produced energy carrier; \(N_{PEC}\) – capacity of the plant for generating the produced energy carrier.

**Figure 1.** The scheme of separate generation of electricity and produced energy carrier.

STP – steam turbine plant; PPEC – plant of produced energy carrier; \(B_{feSTPc}\) – fuel consumption per unit of time for generation of electric power at STP at combined generation; \(N_{ec}\) – electric power transmitted to the consumer at combined generation of electric power and produced energy carrier; \(N_{en}\) – rated electric power of STP; \(B_{mPEC}\) – material consumption for plant of the produced energy carrier; \(N_{PEC}\) – capacity of the plant for generating the produced energy carrier.

**Figure 2.** The scheme of combined generation of electricity and produced energy carrier.

Since different types of energy can be produced at the condensing power plant as additional energy carrier: compressed air, liquefied natural gas, hydrogen, etc., and the energy of different types can be obtained at the output of the generation object, then as an efficiency evaluation criterion of the generation object is taken the exergy efficiency [3].

Exergy efficiency for each scheme of separate and combined generation are respectively determined by expressions:

\[
\eta_{es} = \frac{E_{es} + E_{PEC}}{E_{fe} + E_{mPEC}}
\]

\[
\eta_{es,c} = \frac{E_{ec} + E_{PEC}}{E_{fe} + E_{mPEC}}
\]

(1)
\( \eta_{ex.s} \) and \( \eta_{ex.c} \) – exergy efficiency at separate and combined generation of the electric power and the produced energy carrier respectively; \( E_{ex.s} \) and \( E_{ex.c} \) – exergy of electric power at separate and combined generation of the electric power and the produced energy carrier respectively; \( E_{fes} \) and \( E_{fec} \) – exergy of fuel for electric power generation in case of separate and combined generation of electricity and produced energy carrier, respectively; \( E_{PEC} \) – exergy of the plant's capacity for generation of the produced energy carrier; \( E_{mPEC} \) – exergy of raw materials in a unit of time for generation of the produced energy carrier.

The following conditions were accepted for the study:

– electric power transferred to the consumer at combined and separate generations are the same:
\[ N_{es} = N_{ec} = N_e; \] (3)

– the electric power unclaimed by the consumer at combined generation is completely transferred for generation of the produced energy carrier;

– installations for generation of the produced energy carrier at combined and separate generations are the same;

– the specific fuel consumption for power generation at the reduction of the electric load of the power unit is increasing;

– in case of separate generation, the electric power transmitted to the plant for generation of the produced energy carrier is produced with the same specific fuel consumption as in the case of combined generation.

An analysis of formula (5) shows that the sign of \( \Delta \eta_{ex} \) determines the second bracket of the numerator
\( \left( \frac{(E_{fes} + E_{PEC})}{(E_{fes} + E_{mPEC})} \right) - \left( \frac{(E_{fec} + E_{mPEC})}{(E_{fes} + E_{mPEC})} \right) \).

Expression for fuel exergy in general form is as follows [3]:
\[ E_f = B_f \left[ 1.04 Q_{lc,f} + (h_f - h_0) - T_0 (s_f - s_0) \right] \] (6)

\( B_f \) - fuel consumption per unit time; \( Q_{lc,f} \) - lower calorific value of fuel; \( h_f \) and \( s_f \) - enthalpy and entropy of the fuel flow for the given parameters; \( T_0, h_0 \) and \( s_0 \) - temperature, enthalpy and entropy of the fuel flow at ambient parameters, respectively.

In accordance with the accepted conditions, the properties and physical parameters of the fuel for combined and separate generation are constant, which makes it possible to transform equation (6) by denoting the expression in brackets for a certain constant value of A:
\[ E_f = B_f \cdot A \] (7)

In accordance with the obtained expression (7), the difference between the exergy \( (E_{fes} - E_{fec}) \) can be written in the form:
\[ E_{fes} - E_{fec} = A \cdot B_{fes} - A \cdot B_{fec} = A(B_{fes} - B_{fec}) \] (8)

\( B_{fes} \) and \( B_{fec} \) – fuel consumptions for the production of electricity at separate and combined generation of electricity and produced energy.

These consumptions can be expressed through electric power and specific fuel consumptions:

– at combined generation, the fuel is consumed only for a steam turbine plant having a nominal power \( N_e \) and its flow is determined from the expression:
\[ B_{fes} = b_{fes} \cdot N_r \]

- \( b_{fes} \) specific fuel consumption for electricity generation at the rated load of the power unit; \( N_r \) - rated power of the power unit.

- at separate generation, fuel consumption is defined as the sum of two fuel consumptions: for a steam turbine plant for generating a specified electric power \( N_{es} \) and for generating electricity for driving a plant of produced energy carrier \( N_{PEC} \):

\[ B_{fes} = B_{fesSTPS} + B_{fesPEC} \]

The fuel consumption for a steam turbine plant for generating a specified electric power \( N_{es} \) at separate generation is:

\[ B_{fesSTPS} = b_{fes} \cdot N_{es} \]

\( b_{fes} \) - specific fuel consumption for electricity generation at a specified load of the power unit at separate generation.

The fuel consumption for the production electric power \( N_{PEC} \) for driving a plant of produced energy carrier, taking into account the accepted conditions:

\[ B_{fesPEC} = b_{fes} \cdot N_{PEC} \]

Having expressed the value of the electric power for driving a plant of produced energy carrier, through the rated power of the power unit and the power transferred to the consumer, as:

\[ N_{PEC} = N_r - N_e \]

and substituting this expression into equation (12) can be obtained:

\[ B_{fesPEC} = b_{fes} \cdot (N_r - N_e) \]

After substituting expressions (11) and (14) into expression (10), taking into account condition (3), it is possible to obtain an equation for determining fuel consumption in the system of separate generation of electricity and produced energy carrier:

\[ B_{fes} = b_{fes} \cdot N_e + b_{fes} \cdot (N_r - N_e) \]

After substituting expressions (9) and (15) into expression (8) and some simplifications, it was obtained:

\[ E_{fes} - E_{fes} = AN_e (b_{fes} - b_{fes}) \]

After substituting expression (16) into expression (5), and expressing the constant value of A according to (6), under the accepted conditions, one can obtain an expression for the difference in exergy efficiency in the form:

\[ \Delta \eta_{ex} = \frac{(E_e + E_{PEC}) \cdot (1,04Q_{ic,f} + (h_f - h_0) - T_0 (s_f - s_0))}{(E_{fes} + E_{mPEC}) \cdot (E_{fes} + E_{mPEC} - N_e (b_{fes} - b_{fes})} \]

It can be seen from equation (17) that the sign of the difference in the exergy efficiency will depend on the sign of the difference in the specific fuel consumption for generating electricity at separate and combined generation.

3. Conclusions

Thus, the exergy efficiency of combined generation of electricity and produced energy carrier will be higher in those cases when the specific fuel consumption for power generation at CPP at combined generation will be less than the same index at separate generation. This fact should be performed in almost all cases, since under the accepted conditions, the main equipment of a power plant at combined generation operates under more favorable conditions, i.e. with a rated power at which the specific fuel consumption for the generation of electricity is always lower than when working with a power different from the rated at separate generation of electricity and another produced energy carrier.
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