Heating index for combined-cycle

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Abstract. The technique of the analysis of combined-cycle power plants with binarity coefficient which is less than one is offered. The technique enters a heating indicator. The index characterizes warmth annealing by combined-cycle power plant. Plant is equipped with the steam turbine with heating selection of steam. Plants with afterburning and dual-fuel plants are considered. Interference of again entered index, degrees of binarity, various efficiencies is at each other shown in this article. The heat balance diagrams and the power streams’s integrated charts of combined-cycle plants on the basis of the gas-turbine unit V64.3 are submitted. The calculated quantitative values of an efficiency on power generation on thermal consumption, coefficient of binarity, a heating index, the relative annealing of warmth and other characteristics for some of the actual or being in a stage of the project combined-cycle plants are given.

1. Introduction
Increasing the efficiency of fuel using in power plants is a relevant problem. One of the ways to increase the energy generation efficiency is using of combined-cycle power plants (CCPP) with binarity coefficient which is less than one. Through this, using of solid fuel in combined-cycle is possible [1–4]. Binarity coefficient is determined by the following equation:

\[ \gamma = \frac{Q_{GTU}^C}{Q_{GTU}^C + Q_{STU}^C} = \frac{Q_{GTU}^C}{Q_{CCPP}^C}, \]

where \( Q_{GTU}^C \); \( Q_{STU}^C \), MW – energy supplied to the combined-cycle plant through the combustion chamber of the gas turbine and the steam boiler, respectively.

This index characterizes the amount of energy supplied to the installation through the gas turbine relative to the total energy supplied.

2. Combined-cycle power plant with a coal afterburning
In contrast to the gas turbine combustion chamber where gas is burned, for generating steam of high parameters in the steam boiler can be used any type of fuel, including coal. In the combined cycle technology coal is involved with the efficiency of using unattainable in other technologies of energy generation where coal is used.

The thermodynamic feature of a combined-cycle with binarity less than one is described below. Energy is supplied in two places (Figure 1a). The first one – through the combustion chamber of the gas turbine \( Q_{GTU}^C = Q_{gas} \) to ensure work of the gas turbine cycle (1-2-3-4-1, Figure 1a). The second one – through the steam power boiler \( Q_{CCPP}^C = Q_{coal} \) to ensure high parameters of the generated steam in the steam turbine cycle. The heat flow worked in the gas turbine (\( Q_{out}^{GTU} \)) is also transferred to the water-steam circuit through the waste-heat boiler. Useful product in the form of electricity are obtained both...
in the gas turbine and in the steam turbine units of the combined cycle. In addition, the steam turbine unit has a heat selection that provides heat supply to the consumer $Q_h$ (Figure 1a).

The technological scheme describing thermodynamic approach is presented in Figure 1b. The air enters the compressor of a gas turbine unit (GTU), is compressed and enters with high pressure into the combustion chamber, where its temperature is increased due to the combustion of gas. After this the hot air and the products of combustion of the fuel enter the gas turbine, where they provide the electricity output ($N_{\text{GTU}}$). After gas turbine the exhaust gases is sent to a waste-heat boiler (WHB), where it is used to generate steam of average parameters for a steam turbine unit (STU) with power generation ($N_{\text{STU}}$). At the same time, high parameters of a sharp steam ensure the combustion of fuel (in particular, coal) in a steam boiler (SB), and an additional stream combined with reheating steam (process R-RR, Fig. 1a) and sent to the middle part of the steam turbine unit is generated in the waste heat boiler. Thus, the steam turbine has a wheel space where with steam expansion a flow of steam increases, even if there are bleeds (not shown in Figure 1b). The exhausted steam after the steam turbine enters the condenser (C), where it weeps (process K-K', Figure 1a) and then is transferred to a waste-heat boiler and a steam boiler by the condensate pump (CP) and the feed-water pump (FWP). The regeneration system on the cycle arrangement is represented by a deaerator. In addition, the steam turbine has heat extraction, steam from which is sent to the heating system (HS) to provide heat supply $Q_h$ to the consumer. The presence of the heat recovery boiler and steam boiler in the thermal scheme, which provide parallel steam generation of high and average parameters, determine the name of the installation, as a parallel-type CCPP [5].

![Thermodynamic diagram (a) and thermal scheme (b) of a combined-cycle power plant with a coal afterburning and a binary coefficient less than one.](image)

Heat (energy) supplied to the combined-cycle plant ($Q_{\text{GTU}}$) is provided by the combustion of fuel and is determined by the following equations:

\[
\begin{align*}
Q_{\text{GTU}} &= B_{\text{GTU}} \cdot Q_i^{r,(\text{GTU})}; \\
Q_{\text{STU}} &= B_{\text{STU}} \cdot Q_i^{r,(\text{STU})}; \\
Q_{\text{CCPP}} &= Q_{\text{GTU}} + Q_{\text{STU}},
\end{align*}
\]

where $B$ is the fuel consumer (kg/s; m$^3$ s) and $Q_i^{r}$ is the lower calorific value (MJ/kg; MJ/m$^3$) of the fuel introduced into the GTU and the STU, respectively. In the case when the gas for a GTU and a
steam boiler is a gas with one calorific value \( Q_{\text{GTU}}^{\text{CCPP}} = Q_{\text{STU}}^{\text{CCPP}} \), the equation for determining the binary coefficient:

\[
\gamma = \frac{B_{\text{GTU}}}{B_{\text{GTU}} + B_{\text{STU}}}.
\]  

(3)

Obviously, the binarity coefficient is less than one \((\gamma < 1)\) provided by the combustion of additional fuel in a steam boiler relative to the combustion chamber of a gas turbine. Such units are called combined-cycle power plants with afterburning of fuel. And units where gas is used as fuel in the combustion chamber of a gas turbine and coal in a steam boiler are called dual-fuel units.

The efficiency of the gas turbine unit of the CCPP can be determined by the following equation:

\[
\eta_{\text{GTU}} = \frac{N_{\text{GTU}}}{Q_{\text{GTU}}}.
\]  

(4)

Taking into account the energy conservation law and using the approaches [6], the amount of heat, which is lost in GTU, will be:

\[
Q_{\text{out}}^{\text{GTU}} = Q_{\text{GTU}} - N_{\text{GTU}}.
\]  

(5)

After substitution:

\[
Q_{\text{out}}^{\text{GTU}} = Q_{\text{GTU}} - \eta_{\text{GTU}} \cdot Q_{\text{GTU}} = (1 - \eta_{\text{GTU}}) \cdot Q_{\text{GTU}}.
\]  

(6)

This heat flow is directed to the steam turbine unit of the plant and it will provide the heating temperature of the steam in the waste-heat boiler equal to the exhausted gases temperature from the GTU (in the case there are no losses). In fact, the GTU output heat \( (Q_{\text{out}}^{\text{GTU}}) \) becomes part of the input heat flow for the Rankine steam-water cycle, which is realized in the steam turbine unit. The other part of the input heat flow for the Rankine cycle is heat \( (Q_{\text{STU}}) \) introduced with the fuel into the steam boiler. The efficiency of the steam turbine unit without of heat extraction \( (Q_h = 0) \) is determined by the equation:

\[
\eta_{\text{STU}} = \frac{N_{\text{STU}}}{Q_{\text{GTU}}^{\text{STU}} + Q_{\text{STU}}^{\text{STU}}}.
\]  

(7)

Therefore

\[
N_{\text{STU}} = \eta_{\text{STU}} \cdot (Q_{\text{out}}^{\text{STU}} + Q_{\text{STU}}^{\text{STU}}) = \eta_{\text{STU}} \cdot Q_{\text{out}}^{\text{STU}} + \eta_{\text{STU}} \cdot Q_{\text{STU}}^{\text{STU}} = \eta_{\text{STU}} \cdot (1 - \eta_{\text{GTU}}) \cdot Q_{\text{GTU}}^{\text{STU}} + \eta_{\text{STU}} \cdot Q_{\text{STU}}^{\text{STU}}.
\]  

(8)

Useful energy obtained plant:

\[
N_{\text{CCPP}} = N_{\text{GTU}} + N_{\text{STU}} = \eta_{\text{GTU}} Q_{\text{GTU}}^{\text{STU}} + \eta_{\text{STU}} Q_{\text{STU}}^{\text{STU}} - \eta_{\text{GTU}} \eta_{\text{STU}} Q_{\text{GTU}} + + \eta_{\text{STU}} Q_{\text{STU}} = \eta_{\text{GTU}} Q_{\text{GTU}}^{\text{STU}} + \eta_{\text{STU}} (Q_{\text{GTU}}^{\text{STU}} + Q_{\text{STU}}^{\text{STU}}) - \eta_{\text{STU}} \eta_{\text{GTU}} Q_{\text{GTU}} = \eta_{\text{GTU}} (1 - \eta_{\text{STU}}) Q_{\text{GTU}} + \eta_{\text{STU}} Q_{\text{CCPP}}
\]  

(9)

The efficiency of CCPP can be determined by the equation:

\[
\eta_{\text{CCPP}} = \frac{N_{\text{CCPP}}}{Q_{\text{GTU}} - Q_{\text{STU}} - Q_h}.
\]  

(10)

At the same time, the combined-cycle power plants can work not only by electrical but also by thermal load curve \( (Q_h > 0) \). In this case the efficiency of the steam turbine unit is:

\[
\eta_{\text{STU}} = \frac{N_{\text{STU}}}{Q_{\text{GTU}}^{\text{STU}} + Q_{\text{STU}}^{\text{STU}} - Q_h}.
\]  

(11)

Therefore

\[
N_{\text{STU}} = \eta_{\text{STU}} (Q_{\text{GTU}}^{\text{STU}} + Q_{\text{STU}}^{\text{STU}} - Q_h).
\]  

(12)

\[
N_{\text{CCPP}} = N_{\text{GTU}} + N_{\text{STU}} = \eta_{\text{GTU}} Q_{\text{GTU}}^{\text{STU}} + \eta_{\text{STU}} Q_{\text{STU}}^{\text{STU}} - \eta_{\text{GTU}} \eta_{\text{STU}} Q_{\text{GTU}} + \eta_{\text{STU}} Q_{\text{STU}} - \eta_{\text{STU}} Q_h = \eta_{\text{GTU}} Q_{\text{GTU}}^{\text{STU}} + \eta_{\text{STU}} (Q_{\text{GTU}}^{\text{STU}} + Q_{\text{STU}}^{\text{STU}}) - \eta_{\text{GTU}} \eta_{\text{STU}} Q_{\text{GTU}} + \eta_{\text{STU}} Q_{\text{STU}} - \eta_{\text{STU}} Q_h = \eta_{\text{GTU}} (1 - \eta_{\text{STU}}) Q_{\text{GTU}} + \eta_{\text{STU}} (Q_{\text{CCPP}} - Q_h).
\]  

(13)

Determining the theoretical efficiency of the CCPP as:

\[
\eta_{\text{CCPP}} = \frac{N_{\text{CCPP}}}{Q_{\text{STU}} - Q_h}.
\]  

(14)
will get

\[ \eta_{CCPP} = \frac{\eta_{GTU}(1 - \eta_{STU})Q_{GTU}}{Q_{CCPP} - Q_h} + \frac{\eta_{STU}(Q_{CCPP} - Q_h)}{Q_{CCPP} - Q_h}. \]  

(17)

After substitutions and generations:

\[ \eta_{CCPP} = \eta_{GTU}(1 - \eta_{STU}) \beta + \eta_{STU}. \]  

(18)

In this equation the heating degree of CCPP:

\[ \beta = \frac{Q_{GTU}}{Q_{STU} - Q_h}. \]  

(19)

Heating degree \( \beta \) characterizes the heat supply by the combined-cycle power plant:

\[ \beta = \frac{\gamma Q_{CCPP}}{Q_{CCPP} - Q_h}. \]  

(20)

Where from after generations

\[ \frac{Q_h}{Q_{CCPP}} = \frac{\beta - \gamma}{\beta}. \]  

(21)

Considering that theoretically, in the studied installation \( 0 < \frac{Q_h}{Q_{CCPP}} \leq 1 \), the Heating degree \( \beta \) can take the values \( \beta < 0 \) (Figure 2).

![Figure 2](image)

**Figure 2.** Relative heat supply by the combined-cycle power plant with afterburning of fuel, depending on the heating degree \( \beta \) (a) and the binary coefficient \( \gamma \) (b).

For technically implemented combined-cycle power plants the heating degree \( \beta \) depends on the binary coefficient \( \gamma \) and for plants close to the binary type can take values \( \beta > 1 \). Due to heat flows can be obtained for the needs of heating only in this case (Figure 2a). For plants with a low binary coefficient, in particular for plants with predominant combustion of coal with \( \gamma \leq 0.5 \), \( \beta \) may take values (Figure 2b, shown by hatching)

\[ 0 < \beta \leq 1. \]  

(22)

The relationship between the heating degree \( (\beta) \) and the binary coefficient \( (\gamma) \) of the CCPP is linear and depends on the relative heat supply of the CCPP (the value of the heat extraction). In general, \( \beta \) grows with \( \gamma \) (Figure 3).

Heating CCPP is characterized by the operation of a steam turbine unit in a heat-extraction mode. It is apparent that with the growth of combined electricity generation, characterized by the efficiency of a steam turbine unit increasing (\( \eta_{STU} \)), the heating degree \( (\beta) \) of the CCPP (Figure 4) also grows. At the same time, to ensure high efficiency of the CCPP, should not tend to high \( \beta \) values.

The effect of the gas turbine unit efficiency on the CCPP efficiency is less noticeable than the effect of the heating degree \( \beta \). The greater the quantity of heat extraction (\( \beta \) grows), the higher the
CCPP efficiency (Figure 5). In general, we can say that for the high thermodynamic efficiency of the dual-fuel CCPP, there is should be a powerful gas turbine unit with a relatively small steam turbine, but at the maximum heat extraction. Questions of economic efficiency are not considered in this paper.

**Figure 3.** Dependence of the heating degree ($\beta$) on the binary coefficient ($\gamma$) of the CCPP for different relative output of heat extractions.

**Figure 4.** Influence of the heating degree ($\beta$) and efficiency of a steam-turbine unit operating according to the thermal load curve ($\eta_{STU}$) on the efficiency of the CCPP ($\eta_{CCPP}$).

**Figure 5.** Influence of the gas-turbine unit efficiency ($\eta_{GTU}$) on the CCPP efficiency ($\eta_{CCPP}$) at different values of the heating degree ($\beta$).

### 3. Calculation results
The following are the results of some CCPP schemes calculations with heat extractions (Figures 6–9).
Figure 6. The principle thermal scheme (a) and the enlarged diagram (b) of energy flows of a binary type combined-cycle power plant based on GTU LM2500 + G4 and STU T-14/23.

Figure 7. The principle thermal scheme (a) and the enlarged diagram (b) of energy flows of the combined-cycle power plant based on GTU V64.3 Siemens and STU T-65 / 75-130 on the development of JSC “VTI” with afterburning.

Figure 8. The principle thermal scheme (a) and the enlarged diagram (b) of energy flows of the combined-cycle power plant based on GTU V64.3 Siemens and STU T-65 / 75-130 for the development of JSC “ENKO-center” with afterburning.
Figure 9. The principal thermal scheme and the enlarged diagram of energy flows of the combined-cycle power plant based on GTU V64.3 Siemens and STU T-130 / 160-12.8 with afterburning.

During calculations according to the JSC “VTI” and JSC “ENKO-center” schemes it was taken into account that heat is supplied to the consumer after the waste-heat boiler does not enter the steam turbine unit (table 1).

In general, examples of calculations show that the heating degree can be used for the analysis of CCPP with the heat supply to the consumer.

Table 1. Characteristics of CCPP (using data [3, 5, 7, 8])

| Indicator name | CCPP-90 Omsk | CCPP-230 project JSC «KOTES» | CCPP-145 project JSC «VTI» | CCPP-145 project JSC «ENKO-center» |
|----------------|--------------|-------------------------------|----------------------------|-----------------------------------|
| 1              | Installed capacity, MW | 90   | 230                          | 145                             | 145                               |
| 2              | GTU type      | LM2500 | V64.3a                       | V64.3a                          | V64.3a                           |
| 3              | GTU capacity, MW | 32 (31.8) | 70 (65)                     | 70 (65)                         | 70 (65)                          |
| 4              | STU type      | T-14/20 | T-130 / 160-12.8            | ITT-65 / 75-130                 | ITT-65 / 75-130                  |
| 5              | STU capacity, MW | 20 (20) | 160 (130)                    | 75 (50)                         | 75 (50)                          |
| 6              | Heat extraction, MW | 60   | 163                          | 120                             | 120                              |
| 7              | Fuel, GTU/STU | gas    | gas/gas                      | gas/gas                         | gas/gas                          |
| 8              | Industrial steam | no    | no                           | yes                             | yes                              |
| 9              | Industrial extraction pressure, MPa | –     | –                            | 1.2                             | 1.2                              |
| 10             | Industrial steam through WHB/extraction, MW | –     | –                            | 64/148                          | 100/148                          |
| 11             | GTU efficiency, relative unit | 0.3   | 0.36                         | 0.36                            | 0.36                             |
| 12             | STU efficiency of electricity generation with heat extraction, relative unit | 0.23  | 0.7                          | 0.46                            | 0.49                             |
| 13             | CCPP efficiency of electricity generation with heat extraction, relative unit | 0.55  | 0.79                         | 0.67                            | 0.88                             |
| 14             | Binary coefficient, $\gamma$ | 1     | 0.44                         | 0.4                             | 0.41                             |
| 15             | Heating degree, $\beta$ | 1.39  | 0.72                         | 0.67                            | 0.49                             |
| 16             | Ratio $Q_\text{h}/Q_{\text{CCPP}}$ | 0.28  | 0.38                         | 0.61                            | 0.7                              |
manufacture Siemens;

in parentheses are the values of the design mode;

c for the project JSC «VTI» through WHB is ensured industrial steam with $P = 0.9$ MPa and $t = 350 \degree$C; for the project JSC «ENKO-center» – $P_1 = 2.5$ MPa and $t_1 = 350 \degree$C, $P_2 = 0.9$ MPa and $t_2 = 250 \degree$C.

4. Calculation results

1. The energy research method of combined-cycle power plants with a binary coefficient less than one was developed and presented, the heating degree $\beta$ was introduced.
2. It is shown that, in the general case, the heating degree $\beta > 0$. For dual-fuel plants, in particular with predominant use of coal, $0 < \beta \leq 1$. For the binary type plants $\beta > 1$
3. It is shown that the effect of the heating degree $\beta$ on the combined-cycle power plant efficiency is generally more noticeable than the effect of the GTU efficiency.

References

[1] Peternya Y K The history of the combined cycle cycle in Russia. Available at: http://www.combienergy.ru/stat/900-Istoriya-parogazovogo-cikla-v-Rossii-Perspektivy-razvitiya
[2] Shchinnikov P A, Nozdrenko G V, Borodihin I V et al 2007 Energy issues 13–22
[3] Shchinnikov P A, Nozdrenko G V, Lovcov A A 2002 Thermophysics and aerodynamics 9 445–449
[4] Burov V D, Konakotkin B V, Canev S V 1998 Energy Saving and Water Treatment 37–43
[5] Canev S V, Burov V D, Remezov A N 2002 Gas turbine and combined cycle plants of thermal power plants (Moscow: MEI) p 584
[6] Kirsanova N I 2016 Thermodynamics of combined cycles Energy and heat engineering: collection of scientific papers (Novosibirsk: NGTU) pp 183–188
[7] Shcheglyaev A V 1993 Steam turbines. Theory of the thermal process (Moscow: Energoatomizdat) 1 384 p
[8] Grigor'eva V A, Zorina V M 1989 Thermal and nuclear power plants. Directory (Moscow: Energoatomizdat) 608 p