Increasing efficiency of CCP-based TPP with injection of dry saturated steam from recovery boiler into regenerator

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Abstract. The object of this study is a contact combined-cycle plant with the injection of dry saturated steam into a regenerative air heater and with water heating recovery boiler. Peculiarity of the scheme is that for cooling the turbine flow range and for injection, we used dry saturated steam and the mixing point is a regenerator. In order to reduce heat loss to the environment we additionally inserted water heating recovery boiler. The study was conducted using the software package "Computer analysis system for CCP and GTP combination". We introduced the results of the optional optimization parameters of working fluids, which were made according to the given scheme. Additional useful power increase of CCP occurs due to the use of steam cooling. Efficiency thus reaches 47.52% and the capacity of water heating recovery boiler reaches 2.1 MW. To verify the calculations, we used mathematical modeling method based on graph theory.

In the short term gas turbine and combined-cycle plants should become the main engines for the production of electrical energy, partially replacing a steam-powered capacities. However, the possibility to improve them has not yet been exhausted, because efficiency of manufactured gas turbines is at least 36-40% [1, 2].

Earlier we studied a scheme of CCP-based TPP with the injection of dry saturated steam from the recovery boiler into the regenerator [3, 4]. Among its disadvantages there is high temperature of smoke gases in front of the contact gas cooler, and as a result, an excessive amount of heat discharged into atmosphere. These losses can be reduced further by installing water heating recovery boiler. A further increase in efficiency is achieved through the replacement of air-cooled wheel space by a steam-cooled one. The studied scheme is shown in figure 1.

To determine the thermal performance, we performed calculation using the characteristics of the CCP using the data of AD - 31ST: the mass flow rate of compressed air into the air compressor - 61.0 kg / s; internal efficiency compressor - 0.87; internal efficiency of the turbine - 0.92; mechanical efficiency - 0.98; electric efficiency - 0.97. Effective performance of the base installation was 36.5%, and GTP net power was 20.0 MW at a pressure of compressed air in the compressor of 2.1 MPa and temperature of the gases at the turbine inlet was T3 = 1523.15 K [5].

We examined optimization parameters of the studied scheme with the computer program "Computer analysis system for CCP and GTP combination" [6]. The scheme was to find compression level in an air compressor, which would give us maximum efficiency. The main limiting factor was the temperature difference in the economizer heating surfaces of the steam recovery boiler (Δt_{CCP}≥35 K). Mass fraction of injected steam is 0.1 from the flow of dry gas in the combustion efficiency conditions, the mass fraction of steam cooling is 0.03 from the air flow, compressed in the compressor.
Figure 1. Heat scheme of CCP-based TPP with injected dry saturated steam from recovery boiler into regenerator and with steam cooling:

1 - low pressure compressor (LPC), 2 - air cooler (AC), 3 - high pressure compressor (HPC), 4 - regenerator (R), 5 - combustion chamber (CC), 6 - gas high pressure turbine (HPT), 7 - HPT shaft, 8 - gas low pressure turbine (LPT), 9 - LPT shaft, 10 - electrical generator (EG), 11 - steam recovery boiler (SRB), 12 - economizer (EC), 13 - water heating recovery boiler (WHRB), 14 - heat consumers (HC), 15 - supply-line electric pump (SEP), 16 - impact gas cooler (GC), 17 - air cooler (AC), 18 - circulation electric pump (CirEP), 19 - condensate electric pump (ConEP), 20 - superheated water deaerator (SWD), 21 - feeding electric pump (FEP), 22 - reducing valve (RV), 23 - power-supplying electric pump (PEP).

Figure 2 shows the dependence of the investigated schemes efficiency on the pressure at the outlet of the air compressor.

The calculations showed that the maximum efficiency is achieved by heating temperature of steam-gas mixture in the regenerator to 310 °C, the pressure of the steam-gas mixture at the inlet of the high pressure turbine is 2.4 MPa and 47.52%. Electrical power at CCP was Nccp = 40.5 MW, Qwhrb = 2.1 MW fuel consumption was V = 1.94 kg/s. Characteristics of investigated CCP at different pressures at the outlet of the HPC are given in Table 1.
Figure 2. Efficiency dependence of CCP-based TPP with injected dry saturated steam from recovery boiler into regenerator and with steam cooling on the pressure at the outlet of the HPC at various temperatures in the heating regenerator

Table 1. Characteristics of the study PSU at different pressures at the outlet of the HPC.

| $P_2$ | Nkv | Qp  | Qsrb | Qwhrb | Qge  | Nccp | V       | Efficiency coefficient | FUF | $\Delta t_{ccp}$ |
|-------|-----|-----|------|-------|------|-------|---------|------------------------|-----|-------------------|
| MPa   | MW  | MW  | MW   | MW    | MW   | MW    | kg/c    | %                      | %   | K                 |
| 2.00  | 22.0| 8.2 | 18.8 | 3.9   | 22.9 | 39.5  | 1.94    | 46.42                  | 50.99| 62.3              |
| 2.05  | 22.2| 8.1 | 18.8 | 3.6   | 22.9 | 39.7  | 1.94    | 46.58                  | 50.85| 58.8              |
| 2.10  | 22.4| 8.0 | 18.8 | 3.4   | 22.9 | 39.8  | 1.94    | 46.73                  | 50.71| 55.4              |
| 2.15  | 22.6| 7.9 | 18.8 | 3.1   | 22.9 | 39.9  | 1.94    | 46.88                  | 50.57| 52.1              |
| 2.20  | 22.8| 7.8 | 18.9 | 2.9   | 22.9 | 40.1  | 1.94    | 47.02                  | 50.44| 48.9              |
| 2.25  | 23.0| 7.7 | 18.9 | 2.7   | 22.9 | 40.2  | 1.94    | 47.15                  | 50.30| 45.8              |
| 2.30  | 23.2| 7.5 | 18.9 | 2.5   | 22.9 | 40.3  | 1.94    | 47.28                  | 50.17| 42.8              |
| 2.35  | 23.4| 7.4 | 18.9 | 2.3   | 22.9 | 40.4  | 1.94    | 47.40                  | 50.05| 39.9              |
| 2.40  | 23.6| 7.3 | 18.9 | 2.1   | 22.9 | 40.5  | 1.94    | 47.52                  | 49.92| 37.1              |

$P_2$ is the air pressure at the outlet of the HPC, Nkv is power consumed by an air compressor, Qp is heat power P, Qccp is thermal power of CCP, Qwhrb is thermal power of WHRB, Qge is thermal power of gas equipment, Nccp is useful CCP power, V is fuel flow rate, $\Delta t_{ccp}$ is average temperature difference on the economizer part of CCP.

Mathematical modeling using graph theory is well applicable to GTP and CCP, because it is characterized by clarity and one-parameter constraints [7]. To verify the calculated data of the
examined scheme, we created power flows graphs (figure 3), which is the subgraph to the generalized one [8], and a mathematical model of the device. In the graph, vertices are the elements of the scheme, and arcs are flows of matter and energy. In the matrix the vertices have conventional keys corresponding to the thermal circuit; we additionally introduced key 24 - the consumer of electric energy. As assumptions, the circuit elements 15, 17-23 were not included in the model as their influence is negligible.

![Diagram of power flows](image)

**Figure 3.** The graph of a mathematical model of CCP-based TPP with injected dry saturated steam from recovery boiler into regenerator and with steam cooling.

The equations of the mathematical model of CCP investigated schemes:

for the environment:

\[
N_0 = N_1 \cdot \eta_{01} + N_2 \cdot \eta_{20} + N_3 \cdot \eta_{30} + N_4 \cdot \eta_{40} + N_5 \cdot \eta_{50} + \\
+ N_6 \cdot \eta_{60} + N_7 \cdot \eta_{70} + N_8 \cdot \eta_{80} + N_9 \cdot \eta_{90} + N_{10} \cdot \eta_{100} + \\
+ N_{11} \cdot \eta_{110} + N_{12} \cdot \eta_{120} + N_{13} \cdot \eta_{130} + N_{14} \cdot \eta_{140} + N_{24} \cdot \eta_{240};
\]  

(1)

for low pressure compressor:

\[
N_1 = N_0 \cdot \eta_{01} + N_7 \cdot \eta_{71};
\]  

(2)

for air cooler:

\[
N_2 = N_1 \cdot \eta_{12};
\]  

(3)

for high pressure compressor:

\[
N_3 = N_2 \cdot \eta_{23} + N_7 \cdot \eta_{73};
\]  

(4)

for regenerator:

\[
N_4 = N_3 \cdot \eta_{34} + N_8 \cdot \eta_{84} + N_{11} \cdot \eta_{114};
\]  

(5)

for combustion chamber:

\[
N_5 = N_0 \cdot \eta_{05} + N_4 \cdot \eta_{45};
\]  

(6)

for high pressure turbine:

\[
N_6 = N_5 \cdot \eta_{56};
\]  

(7)
for high pressure turbine shaft:
\[ N_7 = N_6 \cdot \eta_6,7; \]  \hspace{1cm} (8)
for low pressure turbine:
\[ N_8 = N_6 \cdot \eta_6,8; \]  \hspace{1cm} (9)
for low pressure turbine shaft:
\[ N_9 = N_8 \cdot \eta_8,9; \]  \hspace{1cm} (10)
for electrical generator:
\[ N_{10} = N_9 \cdot \eta_9,10; \]  \hspace{1cm} (11)
for steam recovery boiler:
\[ N_{11} = N_4 \cdot \eta_{4,11} + N_{12} \cdot \eta_{12,11}; \]  \hspace{1cm} (12)
for feeding water economizer:
\[ N_{12} = N_{11} \cdot \eta_{11,12} + N_{16} \cdot \eta_{16,12}; \]  \hspace{1cm} (13)
for water heating recovery boiler:
\[ N_{13} = N_{12} \cdot \eta_{12,13}; \]  \hspace{1cm} (14)
for heating consumer:
\[ N_{14} = N_{13} \cdot \eta_{13,14}; \]  \hspace{1cm} (15)
for impact gas cooler:
\[ N_{16} = N_0 \cdot \eta_{0,16} + N_{13} \cdot \eta_{13,16}; \]  \hspace{1cm} (16)
for energy consumer:
\[ N_{24} = N_{10} \cdot \eta_{10,24}; \]  \hspace{1cm} (17)

\[ i, k \] – graph elements’ numbers \((i, k=0, 1, 2, \ldots, 14, 16, 24);\)
\(N_i\) – the sum of energy flow power, ending in the vertice \(i\), MW;
\(\eta_{k,i}\) – the coefficient of energy transfer from the vertice \(k\) to the vertice \(i\):
\[ \eta_{k,i} = \frac{N_{k,i}}{N_k}; \]  \hspace{1cm} (18)
\(N_{k,i}\) – the energy flow power, exiting from the vertice \(k\) and entering the vertice \(i\), MW.
\[ \sum \eta_{k,i} = 1; \]  \hspace{1cm} (19)

We add to the system of equations the correlation between the efficiency of the elements with the corresponding transmission coefficients and the values of the boundary energy flows entering the system \((N_0, \bar{N}_{0.5}, N_{0.16})\). The system of equations (1) - (19) is carried out by successive approximations [9]. As a result, for this setting, the power transmission flow coefficients have been obtained in the fifth approximation with the following values (all coefficients are equal to zero):
\[ \eta_0 = 0.246; \eta_{0.5} = 0.634; \eta_{0.16} = 0.120; \eta_{1.2} = 0.269; \eta_{1.3} = 0.731; \eta_{3.0} = 0.003; \eta_{3.4} = 0.997; \eta_{4.5} = 0.475; \eta_{4.11} = 0.525; \eta_{5.0} = 0.01; \eta_{5.6} = 0.156; \eta_{6.8} = 0.844; \eta_{7.0} = 0.020; \eta_{7.1} = 0.498; \eta_{7.3} = 0.482; \eta_{8.4} = 0.674; \eta_{8.9} = 0.020; \eta_{9.0} = 0.980; \eta_{9.10} = 0.033; \eta_{10.2} = 0.967; \eta_{11.0} = 0.002; \eta_{11.4} = 0.236; \eta_{11.12} = 0.762; \eta_{12.11} = 0.031; \eta_{12.13} = 0.969; \eta_{13.14} = 0.021; \eta_{13.16} = 0.979; \eta_{14.0} = 1; \eta_{15.0} = 0.665; \eta_{16.0} = 0.345; \eta_{24.0} = 1. \]

Solution of graph equations yielded the following values of the power flow graph elements, MW:
\[ N_0 = 134.3; N_1 = 45.2; N_2 = 44.8; N_3 = 153.4; N_4 = 158.0; N_5 = 156.5; N_7 = 24.4; N_8 = 132.1; N_9 = 43.1; N_{10} = 42.2; N_{11} = 83.7; N_{12} = 101.4; N_{13} = 98.3; N_{14} = 2.1; N_{15} = 112.3; N_{24} = 40.8. \]

Substituting the coefficient values obtained for the transfer of energy flows into the matrix, we defined a new value of the efficiency for the combined-cycle power plant in the form of:
\[ \text{Efficiency} = \frac{N_{24} \cdot 100}{N_0 \cdot \eta_{0.5}} = 47.90\% \]
The found efficiency coefficient by using a mathematical model differs by 0.38% from the absolute values obtained by the optimization variant, which indicates the high accuracy of the method.

Conclusions
1. Use of CCP-based TPP with injected dry saturated steam from recovery boiler into regenerator and with steam cooling of the turbine wheel space allows producing electricity at high efficiencies and useful capacities equal to 47.52% and 40.5 MW, respectively. The power of recovery boiler in this case is 2.1 MW.
2. The increase in the efficiency coefficient of CCP-based TPP with injected dry saturated steam from recovery boiler into regenerator in comparison with the baseline GTP (36.5%) was made possible by a more complete inter-cyclic heat recovery and the use of regenerator for steam superheating, and by replacing the air cooling by a steam one.

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