System effectiveness analysis of combined cycle cogeneration plant

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Abstract. Methodology for thermodynamic analysis, fuel efficiency determination, and mathematical economic calculation model of comparative economic effectiveness of combined-cycle cogeneration plant (CCCP) are elaborated. CCCP with a single, dual and triple pressure heat-recovery steam generators (HRSG) are investigated with account for real-time use in Heating System. Employment of CCCP with a triple pressure HRSG ensure high value of system effectiveness. Modes of CCCP, conditional and functional scope of electricity and heat, and condition of construction investment financing of CCCP are main factors have an impact on effectiveness of different schemes of CCCP.

1. Introduction
Thermodynamic improvement of modern combined-cycle cogeneration plant (CCCP) consists in increasing of gas (1600-1700°C) and steam temperature profiles, complicating technological schemes on the basis of multiply-pressure heat-recovery steam generators (HRSGs), applying the technology of combined heat and power. Thermodynamic analysis of cycles of CCCP with multiple-pressure HRSGs keep special aspects. The aspects are steam and heat generation. Separate appliance of the known indices of thermodynamic perfection and heat efficiency of CCCP keep from fuel efficiency determination of total energy system [1 – 3, 8]. Climatic factors, scheme of thermal capacity, use conditions of heat and electrical power, operational reliability of CCCPs in power supply system, solution stability if base techno-economic factors fluctuate are take into account in system approach to bench-making of layout and design of CCCPs.

2. Indices of thermodynamic and fuel efficiency
Distinctions of thermodynamic analysis and fuel efficiency calculations are determinate for most complex design of CCCP with a triple-pressure HRSG and water-to-water heat exchanger (Figure 1a).

Figure 1b shows hypothetical thermodynamic cycle of the CCCP. The main distinction of the cycle is three parts of effective work of gas turbine cycle. The first part \( l_{\text{comb}} \) correspond to high-efficient operation of combined gas turbine cycle beneficial using the heat of exhaust gas of HRSG. The second part \( l_{\text{whe}} \) conform to efficient operation of combined gas turbine cycle beneficial using the heat of exhaust gas of HRSG for water-to-water heat exchanger. The third part \( l_{\text{part}} \) is equivalent to low-efficiency energy generation, which can lead to waste of fuel in CCCP.

True formula

\[
N_{GT} = \Delta N_{GT}^{\text{COMB}} + \Delta N_{GT}^{\text{WHE}} + \Delta N_{GT}^{\text{PART}},
\]

(1)
SH HP, SH IP, SH LP – superheater of high pressure, superheater of intermediate pressure; superheater of low pressure; EV HP, EV IP, EV LP – evaporator of high pressure, evaporator of intermediate pressure; evaporator of low pressure; EC HP, EC IP – economizer of high pressure, economizer of intermediate pressure; CGH – condensate gas heater; WWHE – water-to-water heat exchanger; HPD, IPD, LPD – high pressure drum, intermediate pressure drum, low pressure drum; GSC – gland steam condenser; SE – sealing ejector; STC – steam-turbine condenser; CPW – chemical purified water; Cond – condensate cooler; LH – line heater, HC – heat consumer.

**Figure 1.** Process flow schematic of CCCP with a triple pressure HRSG (a) и hypothetical thermodynamic cycle of the CCCP with triple pressure HRSG (b).

In equation (1) $\Delta N_{GT}^{\text{COMB}} = \phi_{hrsg}N_{GT}$, $\Delta N_{GT}^{\text{WWHE}} = \phi_{wwhe}N_{GT}$, $\Delta N_{GT}^{\text{PART}} = \phi_2N_{GT}$, $\phi_{hrsg}$, $\phi_{wwhe}$, $\phi_2$ – parts of available heat of utilization of combustion products of gas turbine using in HRSG for steam generation, in the water-to-water heat exchanger for water heating-up and diverted in atmosphere; $N_{GT}$ – capacity of gas turbine.

Part of available heat of utilization of combustion products of gas turbine using in HRSG for steam generation are used for heat and power generation in steam-turbine cycle

$$\Delta N_{GT}^{\text{COMB}} = \Delta N_{GT}^{\text{COG}} + \Delta N_{GT}^{\text{PART}}.$$  (2)
In equation (2) \( \Delta N_{GT}^{COG} = \Delta N_{GT}^{COMB} \cdot \frac{\Delta N_{ST}^{COG}}{N_{ST}} \) – part of power of gas turbine cycle is accounted for by cogeneration in steam-turbine cycle; \( \Delta N_{GT}^{PART} \) - part of power of gas turbine cycle is accounted for partial mode of heat and power generation; \( N_{ST} \) – capacity of steam turbine.

Design equation of electric/heat output is

\[
y_e = \frac{\Delta N_{WWHE}^{WTHE} + \Delta N_{GT}^{COG} + \Delta N_{ST}^{COG}}{Q_{WWHE} + Q_{OUT}}.
\]

In equation (3) \( Q_{WWHE} \) – heat energy from water-to-water heat exchanger; \( Q_{OUT} \) – heat energy from heat extraction of steam turbine.

Measure of system fuel economy \( \Delta B_s \) are basis of estimate of fuel economy when using CCGT power plants. The measure of system fuel economy is elaborated in [5,6].

\[
\Delta B_s = (B_{CPS}+B_{RS}) - B_{CCCP} - \Delta B_{REL}.
\]

In equation (4) \( B_{CPS} \) - fuel consumer by condensing power station for electric power generation \( E_{GEN} \); \( B_{RS} \) - fuel consumer by boiler station for heat generation \( Q_{GEN} \); \( B_{CCCP} \) – fuel consumer by CCCP; \( \Delta B_{REL} \) - additional housekeeping overheads for reliability creation of heat and power supply input of customers. The main usability condition is securing of capacity, use conditions of electricity and heat consumption in power system.

Specific system fuel economy when using CCCP is

\[
\beta = \frac{\Delta B_s}{\Delta B_{CCCP}}.
\]

3. Theoretical and calculated research of thermodynamic parameters and energetic characteristics of CCCP

Calculation of thermodynamic parameters and energetic characteristics of CCCP is done for CCCP 110 MW. Basic data of gas turbine: General Electric, type PG6111FA 77 MW, compressor pressure 15.8; compressor flow 203.3 kg/c; exhaust temperature 600 °C. Basic data of steam turbine: type T-25/33.7/6/0.12; triple-pressure HRSG : high steam pressure 8.6 MPa, high steam temperature 535 °C. Registered software package is a base of calculation of design characteristics and steam-production capacity of HRSG. Calculations have done for different modes of operation [4, 5]. Calculation data of energetic characteristics of CCCP is presented in table 1. Heat power of CCCP is 89.5 MW for rated conditions (15 °C). CCCP with triple-pressure HRSG keeps most high value of electrical efficiency \( \eta_{CCCP} \) and electric/heat output \( y_e \). Specific heating surface of CCCP with triple pressure HRSG are 1.21 m² per kW and specific heating surface of CCCP with dual pressure HRSG are 1.19 m² per kW.
Table 1. Calculation data of energetic characteristics of CCCP

| Type of HRSG | Ambient temp., \(^{\circ}\)C | \(N_{GT}\) (MW) | \(N_{ST}\) (MW) | \(N_{CCCP}\) (MW) | \(Q_{WWHE}\) (Gcal/h) | \(Q_{ext}\) (Gcal/h) | \(\eta_{cc}\) | \(\eta_{CCCP}\) |
|--------------|-------------------------------|-----------------|-----------------|-----------------|----------------------|---------------------|-------------|-------------|
| Single-pressure | +30 | 66,70 | 27,08 | 93,78 | 4,87 | 21,58 | 1,8874 | 0,4121 |
| | +15 | 77,42 | 25,59 | 103,02 | 5,00 | 21,59 | 1,9431 | 0,4711 |
| | -1,8 | 85,97 | 22,03 | 108,00 | 5,84 | 70,50 | 0,9837 | 0,4961 |
| | -26 | 89,18 | 19,33 | 108,52 | 6,45 | 70,80 | 0,8455 | 0,5160 |
| | +30 | 66,70 | 31,24 | 97,94 | 4,87 | 21,58 | 2,0215 | 0,4304 |
| | +15 | 77,42 | 31,42 | 108,84 | 5,00 | 21,59 | 2,1155 | 0,4977 |
| | -1,8 | 85,97 | 22,90 | 108,87 | 5,84 | 70,50 | 1,0471 | 0,5001 |
| | -26 | 89,18 | 19,79 | 108,97 | 6,45 | 70,80 | 0,9718 | 0,5182 |
| Dual-pressure | +30 | 66,70 | 31,29 | 97,99 | 4,87 | 21,58 | 2,0353 | 0,4307 |
| | +15 | 77,42 | 33,55 | 110,96 | 5,00 | 21,59 | 2,2256 | 0,5074 |
| | -1,8 | 85,97 | 25,28 | 111,25 | 5,84 | 70,50 | 1,0484 | 0,5110 |
| | -26 | 89,18 | 22,11 | 111,28 | 6,45 | 70,80 | 0,9858 | 0,5291 |

4. Calculation method for reliability measures of CCCP

Operational experiences of CCCPs are shown, that HRSG is the most liable to failures. This fact determines by specific plant operational state, high steam temperature, frequent startup and shutdown, distinctions of steam generation in evaporators and by design features of HRSG. The probabilistic calculation method for simple and integrated reliability measures of elements of HRSG is described in [6]. Analysis of heat stress of metal of heating surface of HRSG and analysis of regular characteristics of applying materials are taken as a basis. Estimation of the HRSG failure-free operation is defined under the conditions of not exceeding the limits of operational and thermal stresses in each of the considered areas. Problem of calculation of design and layout characteristics of HRSG is solved with using of registered software package [7]. Basic layout data of HRSG: for surfaces fin height is 22 mm, fin pitch is 2 mm, tube diameter of economizer is 32 mm, tube diameter of superheater and evaporator is 38 mm, wall thickness is 3 mm. Economizer and evaporator are made of S20, superheater is made of steel F.V. 520. Figure 2 presents the results of calculation of availability factor of different design of CCCPs.
5. Methodology of dividing of usable fuel at the structural-complicated scheme of CCCP

Dividing of usable fuel for heat and electric power generation performed according to methodology, describing in [5]. Delivery of heat energy from heat extraction of steam turbine and of heat energy from water-to-water heat exchanger is considered in the methodology. That's cause of distinction of calculation of ratio of fuel for heat $K_{h,CCCP}$ and electric power generation $K_{e,CCCP}$.

Annual consumption of reference fuel at the CCCP is

$$B_{F,year} = B_{F,(ref),int}^w \tau_w + B_{F,(ref),sum}^w \tau_{sum}.$$  \hspace{1cm} (6)

In equation (6) $B_{F,(ref),int}^w, B_{F,(ref),sum}^w, \tau_w, \tau_{sum}$ - hourly consumption of reference fuel in the combustor chamber of gas turbine (depend on electrical efficiency); time lengths of winter season, inter-season and of summer-time. Part of fuel is consumed for heat generation in the water-to-water heat exchanger. Consequently, value $K_{e,CCCP-U}^{CCP-U}$ without water-to-water heat exchanger is [9]

$$K_{e,CCP-U}^{CCP-U} = \frac{Q_E + \Delta Q_{E,(ext)} + 6.51 B_{CC}}{Q_E + \Delta Q_{E,(ext)} + Q_{OUT} + 6.51 B_{CC}}.$$  \hspace{1cm} (7)

In equation (7) $Q_E = Q_0 - Q_{h}, Q_0$ - total flux of heat to steam turbine; $Q_{h} = Q_{OUT} + Q_{BOP}$ - output of heat from heat extraction of steam turbine to customers, output of heat to balance-of-plant; $\Delta Q_{E,(ext)} = \sum Q_{e,i,j} (1-\xi_i)$ - extra expenses of heat to guarantee of required-power without output of heat; $\xi_i$ - coefficient of output heat value from i-heat extraction of steam turbine; $B_{CC}$ - annual fuel consumption in the combustor chamber of gas turbine.

Part of fuel is consumed for electric power generation in combustion-gas turbine [9]

$$K_{e,GTCP}^{GTCP} = \frac{B_{CC}}{0.16 \cdot Q_{OUT} + B_{CC}}.$$  \hspace{1cm} (8)

In equation (8) $Q_{OUT}$ - output of heat without balance-of-plant.
Part of fuel is consumed for electric power generation in the cases of exploitation of CCGT power plants with water-to-water heat exchanger by reference to specific features

\[ K_{CCCP}^E = \frac{Q_E + \Delta Q_{E(out)} + 6.51B_{CC} \cdot K_{GTCP}^E}{Q_E + \Delta Q_{E(out)} + Q_{OUT} + 6.51B_{CC} \cdot K_{GTCP}^E}. \]  

Consequently, fuel consumption to electric power generation is

\[ B_{CCCP}^E = B_{CCCP} \cdot K_{CCCP}^E = B_{CC} \cdot K_{GTCP}^E \cdot K_{CCCP}^E. \]  

Fuel consumption to heat generation is sum of fuel consumption in the gas turbine cycle to heat generation in water-to-water heat exchanger \( B_{WWHE}^Q \) and fuel consumption in CCCP cycle with heat extraction \( B_{CCCP}^Q \).

Then following ratios are true

\[ B_{CCCP}^Q = B_{CCCP} \cdot (1 - K_{CCCP}^E) = B_{CC} \cdot K_{GTCP}^E \cdot (1 - K_{E}^C). \]  

6. Calculation of extra expenses to guarantee of reliability index of energy provision

Definition of specific system fuel economy and comparison of different schemes of CCCP have done with guarantee of reliability index of energy provision \( F \). Consequently, relevance of extra expenses to operability of emergency backup is necessary. Extra expenses of fuel to operability of emergency backup in electric energy system is \([5,6,10]\)

\[ \Delta B_{REL}^E = r \cdot N_f (1 - K_{AF}) \tau_{sot} (\sigma_{RES} - \sigma_{RES}^E). \]  

In equation (14) \( r \) – value of emergency backup in electric energy system \( N_f \); \( K_{AF} \) – availability factor of CCCP; \( \tau_{sot} \) - scheduled operating time of CCCP; \( \sigma_{RES}^E, \sigma_{RES} \) - specific fuel consumption to electric power output by emergency backup.

Extra expenses of fuel to operability of emergency backup in heat supply system is \([5,6]\)

\[ \Delta B_{REL}^Q = \sum_{j=1}^{m} \tau_j \cdot Q_j^{CCGT} (1 - K_{AF(Q)}) (\sigma_{RES}^Q - \sigma_{RES}^Q). \]  

In equation (15) \( \tau_j \) – scheduled operating time of CCGT with heat duty \( Q_j \); \( K_{AF(Q)} \) availability factor of CCCP; \( \sigma_{RES}^Q, \sigma_{RES}^Q \) - specific fuel consumption to heat output by reserve boiler station and by CCCP.

7. Conclusion

Electrical efficiency of CCCP with a single pressure HRSG is 0.595, with a dual pressure HRSG is 0.602, with a triple pressure HRSG is 0.609. Specific fuel consumption to electric power output is 206.8 g/ kWh (CCCP with single pressure HRSG), 204.2 g/ kWh (CCCP with dual pressure HRSG), 201.7 g/ kWh (CCCP with triple pressure HRSG). Specific fuel consumption to heat output is 100.1kg/Gcal (CCCP with single pressure HRSG), 95.7 kg/Gcal (CCCP with dual pressure HRSG), 92.7 kg/Gcal (CCCP with triple pressure HRSG).

Employment of CCCP with triple pressure HRSG ensure economic fuel efficiency within the order of 27.0-30.5 percent compared with separate electrical supply. Economic fuel efficiency varies with schemes, modes, reliability measures and other factors. CCCP with triple pressure...
HRSG allows for increase specific system fuel economy by 5.5 percent in comparison with CCCP with dual pressure HRSG and by 12.1 percent in comparison with CCCP with single pressure HRSG.

The probabilistic calculation method for simple and integrated reliability measures of elements of structural-complicated CCCP is described. Exploitation of CCCP with triple pressure HRSG result in an increase in accident station rate within the order of 0.035-0.051 in comparison with CCCP with single pressure HRSG is established by theoretical studies. Hence, design of CCCP with triple pressure HRSG is preferable.

8. References
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