Feedwater heating in wasteheat boiler with exhaust gases from gas-turbine power unit

A A Kudinov, S K Ziganshina and K R Khusainov

Samara State Technical University, ul. Molodogvadreiskaya 244, Samara, 443100, Russian Federation

E-mail: tes@samgtu.ru

Abstract. In order to increase cost effectiveness of steam-gas power station, it was suggested to place heat exchange surface in backend part of wasteheat boiler downstream of condensate gas pre-heater to heat feedwater before it is transferred to chemical treatment. Estimations have been made for steam-gas unit PGU-450. In process conditions of steam-gas unit operation, wasteheat boiler energy conversion efficiency increases from 82.65% to 84.97% (by 2.32%) when gas feedwater heater is installed in its low-temperature area. In addition to this, steam-gas unit efficiency increases from 52.99% to 53.53% (by 0.54%) and specific consumption of reference fuel for power generation is reduced by 1.01% (from 232.12 to 229.78 g/(kWt·h)). Savings of reference fuel in monetary terms for steam-gas unit with the capacity of 452.35 MWt and running time of 6500 h/year and reference fuel priced at 3000 rub/t of reference fuel are amount to 20 million 640 thousand rubles per year.

1. Introduction

The Energy Strategy of the Russian Federation within Russian energy industry for period till 2030 covers construction and commissioning of wasteheat-type steam-gas units containing one or several gas-turbine units, wasteheat boilers and steam turbine. This trend in development of Russian energy industry is stipulated by high efficiency of wasteheat steam-gas units in power generation [1, 2, 3]. In addition to this, steam-gas units are less harmful for environment compared to conventional steam-power units due to utilization of natural gas that constitutes 60% of fuel used in Russian energy industry, as primary fuel type, and relatively low consumption of cooling water [8, 10]. Construction and commissioning of wasteheat steam-gas units is the main trend in development of both Russian and global energy industry [6, 9].

Heat effectiveness of steam-gas units depends on perfection level of gas-turbine units, steam turbine, and wasteheat boilers it includes. The efficiency of wasteheat boiler in steam-gas units is influenced by temperature value of output gases exiting its convection pass. Heat extraction of output gases in gas-turbine units is generally performed at quite high temperature (105–110 °C) that stipulates relatively low heat efficiency of wasteheat boiler (less than 85%). Therefore, one of the ways to increase efficiency of wasteheat boiler and effectiveness of wasteheat-type steam-gas units is increasing number of convective heating surfaces at wasteheat boilers in order to reduce temperature of output gases in gas-turbine units.

2. Experimental

To increase effectiveness of gas-turbine unit wasteheat boiler via reduction of output gases temperature, it is suggested to install additionally a heat-exchanging surface for heating feed ("raw") water up to 35-
40 °C in its backend part before the water is transferred for chemical treatment at steam-gas power station (figure 1).

![Figure 1](image-url)  
**Figure 1.** Cycle diagram of steam-gas unit PGU-450 featuring feedwater heating in low-temperature area of wasteheat boiler:

TC – turbocompressor; CC – combustion chamber; GT – gas turbine; EG – electric generator; HPSH, LPSH – superheaters of high and low pressure; HPE, LPE – evaporators high and low pressure; HPWE – high-pressure economizer; GCH, GCWH – gas heaters condensate and source water; D – deaerator; K – condensator; CP – condensate pump; RCP – recirculation pump portion of the turbine condensate; CWC – chemical water clearing.

As an example here we examine wasteheat type two-circuit steam-gas unit PGU-450 of Saint Petersburg North-Western Power Station that consists of two gas-turbine units Siemens V94.2 with the capacity 157 MWt each, two two-circuit wasteheat boilers P-90 PMZ and one steam turbine KT-150-8 LMZ. The electrical capacity of the installed equipment in condensing mode is 450 MWt [4, 5].

PGU-450 Power Unit operates the following way. External air after the particulate cleaning stage in compound air cleaning device (not shown at figure 1) is transferred to turbo compressor of gas turbine unit where the process of compressing it to specified parameters is performed. The compressed air is split in two streams. The first stream (primary air) with flow rate $G_{W1}$ is supplied to gas-turbine unit combustion chamber and engages in combustion of gas fuel generating combustion products heated to high temperature that have the second stream of compressed process air (secondary air) admixed to them with flow rate $G_{W2}$. As a result of mixing combustion products with secondary air, gases are formed that come into flow channel of gas turbine with initial temperature $t'_{GT}$ and flow rate $G_b$. In the gas turbine, as a result of expanding gas stream, work is done and spent to drive electrical generator and turbo
compressor of gas-turbine unit. The gases exhausted in turbine come to two-circuit wasteheat boiler where gas pre-heater of "raw" water is installed to transfer its heat to steam and water. Gases cooled in wasteheat boiler are discharged to gas stack.

In steam two-circuit wasteheat boiler two pressures of water vapor (high and low) are formed and superheated, and each of them is supplied to the respective cylinder of steam-gas unit. The steam exhausted in turbine condenses in condenser, the condensate is transported through wasteheat boiler of condensate gas preheater and is sent to deaerator. After deaerator, the general flow of feeding water is divided into two streams, and each of them come to the respective flowing circuit of wasteheat boiler. Recycling line is provided to pre-heat water before condensate gas pre-heater (to 60 °C).

In order to estimate cost effectiveness of applying feedwater heating in wasteheat boiler, thermal calculation for PGU-450 operation in condensation mode was performed for various temperatures of external air, the method outlined in [7, 8] was taken as the basis (see Table 1).

From equations of thermal balance for heating surfaces of wasteheat boiler, gas enthalpy is calculated:

after high- and low-pressure steam superheaters

\[ h_{\text{HP}} = h_{\text{GT}} - D_{0}^{\text{HP}} (h_{0}^{\text{HP}} - h_{S(\text{HP})}^{\text{HPE}}) / G_{e}; \]  

(1)

high-pressure water economizer

\[ h_{\text{HPE}} = h_{\text{HPE}} - D_{0}^{\text{HP}} (h_{D}^{\text{HPE}} - h_{D}^{\text{W}}); \]  

(2)

condensate gas pre-heater

\[ h_{\text{GCH}} = h_{\text{GCH}} - (h_{0}^{\text{GCH}} - h_{0}^{\text{W}}) / G_{e}; \]  

(3)

where \( h_{0}^{\text{HP}} \), \( h_{0}^{\text{LP}} \) – enthalpies of high- and low-pressure superheated steam; \( h_{S(\text{HP})}^{\text{HPE}} \), \( h_{S(\text{LP})}^{\text{HPE}} \) – enthalpies of steam at saturation temperature in high- and low-pressure drums; \( h_{D}^{\text{HP}} \) – enthalpy of high-pressure circuit feeding water; \( h_{D}^{\text{W}} \) – enthalpy of water before deaerator; \( h_{0}^{\text{GCH}} \) – enthalpy of water before condensate gas pre-heater; \( D_{0}^{\text{HP}} \) and \( D_{0}^{\text{LP}} \) – flow rates of high- and low-pressure steam; \( G_{\text{GCH}} = D_{0}^{\text{HP}} + D_{0}^{\text{LP}} - 0,5D_{D} + G_{e} + 0,5G_{\text{cw}} \) – flow rate of water through condensate gas pre-heater; \( D_{0}^{\text{LP}} \) and \( G_{e} \) – flow rates of steam for deaerator and water for recycling.

From equations of thermal balance for each evaporator, flow rates of high- and low-pressure steam are deduced:

\[ D_{0}^{\text{LP}} = G_{e} (h_{\text{HPE}} - h_{0}^{\text{LP}}); \]  

(5)

\[ D_{0}^{\text{LP}} = G_{e} (h_{\text{HPE}} - h_{0}^{\text{LP}}) / h_{S(\text{LP})}^{\text{HPE}} - h_{D}^{\text{LP}}. \]  

(6)

Here \( h_{D}^{\text{LP}} \) - enthalpy of low-pressure circuit feeding water.

Water enthalpy in mixing area before condensate pumps:

\[ h_{\text{mix}} = G_{c} h_{c} + G_{\text{cw}} h_{\text{cw}} / G_{c} + G_{\text{cw}}, \]  

(7)

where \( h_{\text{GCH}} \) – flow rate of turbine condensate after steam turbine condenser; \( G_{c} = 2D_{0}^{\text{HP}} + D_{0}^{\text{LP}} - D_{D} \) – flow rate of turbine condensate after steam turbine condenser; \( G_{\text{cw}} = 0,05G_{c} \) – flow rate of chemically desalinated water taken with account of internal losses of steam and water in Brayton-Rankine cycle; \( h_{c} \) – condensate enthalpy after steam turbine condenser; \( h_{\text{cw}} \) – enthalpy of chemically desalinated water.
Enthalpy of gases on exit from wasteheat boiler is determined from the following formula:

\[ h_{HRSQ}^* - h_{GCH}^* = G_{SW} (h_{GCWH}^* - h_{GCH}^*) / G_g, \]

where \( h_{GCH}^* \) – enthalpy of gases on exit from condensate gas pre-heater; \( G_g \), \( G_{sw} \) – flow rates of gases and feedwater; \( h_{GCWH}^*, h_{GCH}^* \) – water enthalpy on entry to and exit from gas pre-heater, respectively. Temperature of gases on exit from wasteheat boiler \( t_{HRSQ}^* \) is determined from enthalpy of feedwater on exit from feedwater gas pre-heater.

Efficiency of wasteheat boiler depends on temperature of gases on entry to wasteheat boiler and on exit from its convection pass as well as on temperature of external air:

\[ \eta_{HRSQ} = \left( t_{HRSQ}^* - t_{HRSQ} \right) / \left( t_{HRSQ} - t_{air} \right), \]

where \( t_{HRSQ}, t_{HRSQ}^* \) – temperature of gases on entry to and exit from wasteheat boiler, respectively; \( t_{air} \) – temperature of external air.

Additional cooling of gas-turbine unit exhaust gases in feedwater gas pre-heater increases heat efficiency of wasteheat boiler:

\[ \Delta \eta_{HRSQ} = \left( t_{HRSQ}^* - t_{GSWH}^* \right) / \left( t_{HRSQ} - t_{air} \right) - \frac{t_{HRSQ}^* - t_{GCH}^*}{t_{HRSQ} - t_{GCWH}} = \eta_{HRSQ}^* - \eta_{HRSQ}, \]

here \( t_{GCH}^*, t_{GSWH}^* \) – temperature of gases after two-circuit wasteheat boiler condensate and feedwater gas pre-heaters, respectively; \( \eta_{HRSQ}^*, \eta_{HRSQ} \) – wasteheat boiler efficiency values with and without feedwater gas pre-heater.

To increase the efficiency of the combined cycle plant:

\[ \Delta \eta_{PGU} = \left[ \eta_{GTU} + (1 - \eta_{GTU}) \eta_{HRSQ} \eta_{IST} \right] - \left[ \eta_{GTU} + (1 - \eta_{GTU}) \eta_{HRSQ} \eta_{IST} \right]. \]

3. Results and Discussions

Comparative analysis of the main performance indicators of PGU-450 in the implementation of the source water heating in CU and without its use is presented in table 1.

Calculations were performed with the following input data: pressure of water steam at the entry to flow channel of steam turbine high pressure cylinder – 8.2 MPa; steam pressure at the entry to flow channel of low pressure cylinder – 0.7 MPa; pressure in steam turbine condenser – 5 kPa; electric efficiency of gas-turbine unit – 34.4%; temperature of gases before wasteheat boiler – 537 °C; flow rate of fuel to combustion chamber of single gas-turbine unit – 9.15 kg/s.

4. Conclusion

It is suggested to place heat-exchange surface for feedwater heating before it is transferred to chemical treatment in wasteheat boiler backend part downstream of condensate gas pre-heater. Thermal calculation is performed for PGU-450 with two-circuit wasteheat boilers with and without utilization of feedwater heating in wasteheat boiler. With feedwater gas pre-heater installed in wasteheat boiler low-temperature area its efficiency increases from 82.65 to 85.27% (by 2.62%), in addition to that, steam-gas unit efficiency increases from 52.99 to 53.54% (by 0.55%) and specific consumption of reference fuel for power generation decreases from 232.12 to 229.73 g/(kW·h) (by 1.03%). Cost effectiveness due to feedwater pre-heating in backend part of PGU-450 wasteheat boilers before it is transferred to chemical treatment amounts to 21 million 82 thousand RUB per year.
Table 1. Comparative analysis of the main performance indicators of PGU-450.

| Parameter name, unit of measurement | Calculated value of the parameter |
|-------------------------------------|----------------------------------|
|                                      | t<sub>air</sub>, °C               |
|                                      | -30                              |
|                                      | -20                              |
|                                      | -10                              |
|                                      | 0                                |
|                                      | +10                              |
|                                      | +20                              |
|                                      | +30                              |

PGU-450 without heating the source water in the heat recovery boiler

|                                      | Gas consumption of gas turbines, kg/s |
|-------------------------------------|--------------------------------------|
|                                      | 571.7                                |
|                                      | 557.2                                |
|                                      | 542.6                                |
|                                      | 528.0                                |
|                                      | 513.5                                |
|                                      | 498.8                                |
|                                      | 484.2                                |
| t<sub>HRSQ</sub> -°C                | 108                                  |
|                                      | 107.4                                |
|                                      | 106.8                                |
|                                      | 106.4                                |
|                                      | 105.9                                |
|                                      | 105.3                                |
|                                      | 104.9                                |
| Efficience HRSQ, %                  | 74.96                                |
|                                      | 76.61                                |
|                                      | 78.3                                |
|                                      | 79.99                                |
|                                      | 81.74                                |
|                                      | 83.56                                |
|                                      | 85.38                                |
| Efficience GTU, %                   | 37.27                                |
|                                      | 36.64                                |
|                                      | 36.0                                |
|                                      | 35.36                                |
|                                      | 34.72                                |
|                                      | 34.08                                |
|                                      | 34.44                                |
| Efficience ST, %                    | 33.69                                |
|                                      | 33.82                                |
|                                      | 33.96                                |
|                                      | 34.09                                |
|                                      | 34.22                                |
|                                      | 34.34                                |
|                                      | 34.47                                |
| Efficience PGU, %                   | 53.11                                |
|                                      | 53.08                                |
|                                      | 53.06                                |
|                                      | 53.03                                |
|                                      | 53                                |
|                                      | 52.98                                |
|                                      | 52.97                                |
| b<sub>conv</sub>, g/(kW·h)          | 231.59                              |
|                                      | 231.73                              |
|                                      | 231.81                              |
|                                      | 231.94                              |
|                                      | 232.08                              |
|                                      | 232.16                              |
|                                      | 232.21                              |

PGU-450 with heating of the source water in the GTU heat recovery boiler

|                                      | Water consumption per waste heat recovery boiler, kg/s |
|-------------------------------------|-------------------------------------------------------|
|                                      | 45.79                                  |
|                                      | 45.72                                  |
|                                      | 45.65                                  |
|                                      | 45.57                                  |
|                                      | 45.49                                  |
|                                      | 45.42                                  |
|                                      | 45.33                                  |
| t<sub>HRSQ</sub> -°C                | 95.61                                  |
|                                      | 94.89                                  |
|                                      | 94.09                                  |
|                                      | 93.22                                  |
|                                      | 92.36                                  |
|                                      | 91.49                                  |
|                                      | 90.65                                  |
| Efficience HRSQ, %                  | 77.21                                  |
|                                      | 78.91                                  |
|                                      | 80.66                                  |
|                                      | 82.47                                  |
|                                      | 84.32                                  |
|                                      | 86.22                                  |
|                                      | 88.16                                  |
| Efficience PGU, %                   | 53.67                                  |
|                                      | 53.63                                  |
|                                      | 53.6                                  |
|                                      | 53.57                                  |
|                                      | 53.55                                  |
|                                      | 53.53                                  |
|                                      | 53.52                                  |
| b<sub>conv</sub>, g/(kW·h)          | 229.18                                 |
|                                      | 229.35                                 |
|                                      | 229.48                                 |
|                                      | 229.61                                 |
|                                      | 229.69                                 |
|                                      | 229.78                                 |
|                                      | 229.82                                 |

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