Energy Survey of the Cogeneration Plant

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1 Introduction

The designed installed electrical capacity of the power plant (power unit) is 8 MW, the thermal capacity is at least 8 MW. The electric power is generated with eight gas-fired generating sets (GPUs). The main technical characteristics of the gas reciprocating engines are shown in Table 1.

The fuel used is natural gas.

Thermal power is generated by four power generating units through recuperation of heat coming from the high-temperature cooling circuit of the hot-gas reciprocating engine and the exhaust heat, for which each GPU is equipped with plate-type heat-exchangers and a waste-heat boiler [1–12].

The main technical characteristics of the heat recovery system equipment are shown in Table 2.

The waste-heat recovery system of the power generating unit includes two circuits from each of the four GPUs and grid water pipelines.

The first circuit of the waste-heat recovery system is the high-temperature cooling loop for the generator gas reciprocating engine. In the first circuit, heat extraction from the engine cooling jacket takes place. The second circuit of the GPU heat recovery system is formed with the engine exhaust gas recovery boiler, heat exchanger (heated side), grid plate-type heat-exchangers, piping system, and shut-off valves.

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Table 1 Main technical characteristics of gas reciprocating engines

Name	Nominal power (kW)	Motor	Frequency revolutions (RPM)	Generator voltage
Gas-fired generating set (GPU)	1750	Cummins QSV91G	1500	6.3 kV, 50 Hz

Table 2 Main technical characteristics of the heat recovery system equipment

Name	Specifications	Number (pcs)	Note
Shell-and-tube heat recovery boiler	Nominal power 1054 kW	4	
GPU plate-type heat exchanger "Ridan"	696 kW, 109 plates	4	Heat transfer from the first to the second circuit
Plate-type heat exchanger in the heat supply unit "Ridan"	7000 kW, 217 plates	3	Heat transfer from the second circuit to the grid water
Pump in the heat supply unit GRUNDFOS NB 100-200/192	$Q = 301.7$ m^3/h, $H =$ 40.2 mH_2O $N = 45$ kW, $n =$ 2970 rpm	2	

2 Methods

Thermal power generation in each circuit is defined using a formula, kcal/h [13–22]:

$$Q = G \cdot \rho \cdot c \cdot (t_1 - t_2), (1)$$

where G—heating medium rate, m^3/h; ρ—density of the heating medium, kg/m^3, c—heat capacity of the heating medium, kcal/(kg °C); t_1—heating medium temperature at the inlet to the heat exchanger or the recovery boiler, °C; t_2—heating medium temperature at the output from the heat exchanger or the recovery boiler, °C.

Thermal power losses at the non-insulated pipeline section behind the recovery boiler to the heat-exchangers of the heat supply unit are defined according to Formula (1), where t_1—temperature of the heating medium at the beginning of the pipeline section, t_2—temperature of the heating medium at the end of the pipeline section, °C.

Thermal power generated with one GPU is defined using a formula, kcal/h:

$$Q_{\text{GPU}} = Q_{II} + Q_{r-b} - Q_n,$$

where Q_{II}—thermal power generated with a GPU for the second circuit, kcal/h; Q_{r-b}—thermal power generated with a recovery boiler, kcal/h; Q_n—thermal power losses at the non-insulated pipeline section, kcal/h.

3 Results

Two power units were surveyed at 25% load mode: GPU No. 1 and No. 2. The measurements were taken at the outside temperature of −7 °C. The indicators obtained through the instrumental survey of the GPU 1–2 recovery system are shown in Table 3.

Thermal power generated with the heat exchanger of GPU No. 2 for the second circuit:

$$Q_{II} = 71 \cdot 1066 \cdot 0.69 \cdot (56.9 - 51.7) = 271,559\,\text{kcal/h}$$

Thermal power generated with the recovery boiler:

$$Q_{r-b} = 71 \cdot 1061 \cdot 0.69 \cdot (66.4 - 56.9) = 493,723\,\text{kcal/h}$$

Losses of thermal power at the non-insulated pipeline section:

$$Q_n = 71 \cdot 1058 \cdot 0.69 \cdot (66.4 - 64.5) = 94,335\,\text{kcal/h}$$

Thermal power generated with GPU 2:

$$Q_{\text{GPU No.2}} = 271,559 + 493,723 - 94,335 = 670,946\,\text{kcal/h},\ \text{or}\,7,802\,\text{kW h}$$

At the time of the survey, thermal power was generated with GPU No.1, No.2, No.3 and No.4. The thermal power production at all the GPUs is about the same and equals in aggregate:

$$\begin{aligned}\sum Q &= (Q_{\text{GPU No.1}} + Q_{\text{GPU No.2}}) \cdot 2 = (648,546 + 670,946) \cdot 2 \\ &= 2,638,984\,\text{kcal/h},\ \text{or}\,30,686\,\text{kW h}\end{aligned}$$

The thermal power consumption to cover in-house needs of the power plant is:

$$Q_c = 23 \cdot 1068 \cdot 0.69 \cdot (51.8 - 51.0) = 13,560\,\text{kcal/h}$$

The delivery of thermal energy for heating the consumers is:

$$Q = \sum Q - Q_c = 2,638,984 - 13,560 = 2,625,424\,\text{kcal/h}$$

Table 3 The indicators obtained through the instrumental survey of the GPU 1–2 recovery system

Name	Indicators GPU No. 1	Indicators GPU No. 2
Gas consumption (STCm^3/h)	201.2	205.9
Electric power generation (kW h)	518.2	536.4
First circuit		
Coolant flow through the power generating unit (m^3/h)	39.4	39.4
Coolant temperature at the inlet to the power generator heat exchanger (°C)	65.6	65.4
Coolant temperature at the outlet from the power generator heat exchanger (°C)	57.3	57.4
Second circuit		
Coolant flow through the power generator heat exchanger (m^3/h)	68.0	71.0
Coolant temperature at the inlet to the power generator heat exchanger (°C)	51.7	51.7
Coolant temperature at the outlet from the power generator heat exchanger (°C)	57.3	56.9
Recovery boiler		
Coolant temperature at the inlet to the recovery boiler (°C)	57.3	56.9
Coolant temperature at the outlet from the recovery boiler (°C)	66.7	66.4
Coolant temperature at the end of the non-insulated section (°C)	64.7	64.5
Temperature and composition of the exhaust gases behind the power generator		
– exhaust gas temperature (°C)	544	546
– carbon dioxide CO_2 (%)	6.5	7.1
– oxygen O_2 (%)	9.2	8.6
– carbon monoxide CO (ppm)	847	843
– nitrogen oxide NO_x (ppm)	163	1134
– excess air ratio α	1.70	1.61
Temperature of exhaust gases behind the recovery boiler (°C)	84	86
Heat supply unit		

(continued)

The thermal power generation and delivery for heating the consumers in the heat supply unit from Heat exchangers No. 2 and No. 3 is determined through the formula:

$$Q = Q_{\mathrm{No.2}} + Q_{\mathrm{No.3}}\ \mathrm{kcal/h}$$
$$Q = 271{,}000 \cdot 1 \cdot (49.1 - 44.4) + 263{,}000 \cdot 1 \cdot (49.4 - 44.4)$$
$$= 2{,}588{,}700\ \mathrm{kcal/h},\ \text{or}\ 2.59\ \mathrm{Gcal/h}.$$

Imbalance of the heat delivery for heating the consumers is:

Table 3 (continued)

Name	Indicators GPU No. 1	Indicators GPU No. 2
Total flow of the cooling liquid (tosol) into the common secondary manifold at all the GPUs (m^3/h)	300	300
Temperature of the cooling liquid (tosol) at the inlet to the common secondary manifold (°C)	64.6	64.6
Temperature of the cooling liquid (tosol) at the outlet from the common secondary manifold (°C)	51.9	51.9
Total flow of the coolant (water) into the common manifold of the consumers' network loop (m^3/h)	534	534
Coolant (water) flow through Heat exchanger No. 2 (m^3/h)	271	271
Coolant (water) temperature at the inlet to Heat exchanger No. 2 (°C)	44.4	44.4
Coolant (water) temperature at the outlet from Heat exchanger No. 2 (°C)	49.1	49.1
Temperature of the cooling liquid (tosol) at the inlet to Heat exchanger No. 2 (°C)	64.6	64.6
Temperature of the cooling liquid (tosol) at the outlet from Heat exchanger No. 2 (°C)	51.9	51.9
Coolant (water) flow through Heat exchanger No. 3 (m^3/h)	263	263
Coolant (water) temperature at the inlet to Heat exchanger No. 3 (°C)	44.4	44.4
Coolant (water) temperature at the outlet from Heat exchanger No. 3 (°C)	49.4	49.4
Temperature of the cooling liquid (tosol) at the inlet to Heat exchanger No. 3 (°C)	64.6	64.6
Temperature of the cooling liquid (tosol) at the outlet from Heat exchanger No. 3 (°C)	51.9	51.9
Consumption of the cooling liquid (tosol) to cover in-house needs (m^3/h)	23	23
Temperature of the cooling liquid (tosol) to heat the utilities (°C)	51.8	51.8
Temperature of the cooling liquid (tosol) from heating the utilities (°C)	51.0	51.0

$$2,625,424 - 2,588,700 = 36,724\,\text{kcal/h}, \text{ or } 1.4\%$$

The delivery of thermal energy for heating the consumers according to static instruments is 2.36 Gcal/h, the resulting value of the instrumental survey is 2.59 Gcal/h.

4 Discussion

The specific fuel consumption for electric power generation by GPU No. 1 (excluding thermal power generation) is:

$$b_s = \frac{B}{Q_{\mathrm{GPU\,No.1}}} = \frac{201.2}{518.2} = 0.388\,\mathrm{STCm^3/kW}$$

where B—natural gas flow, STCm^3/h; $Q_{\mathrm{GPU\,No.1}}$—electric power generation, kW h.

With the power plant running in a combined mode (both electric and thermal power generation), the specific fuel consumption for the electric and thermal power in GPU 1 is equal to:

$$b_s = \frac{B}{\sum Q_{\mathrm{GPU\,No.1}}} = \frac{201.2}{518.2 + 754.1} = 0.158\,\mathrm{STCm^3/kW}$$

where $\sum Q_{\mathrm{GPU\,No.1}}$—generation of electric and thermal power, kW h,

- 518.2 kW h—electric power generated with GPU No. 1,
- 518.2 kW h—thermal power generated with GPU No. 1.

The aggregate electric and thermal power generated with GPU No. 1 amounts to 518.2 + 754.1 = 1272.3 kW h. In percentage correlation, the generated electric power made up 40.7%; the generated thermal power—59.3%.

The specific fuel consumption for electric power generation by GPU No. 2 (excluding thermal power generation) is:

$$b_s = \frac{B}{Q_{\mathrm{GPU\,No.2}}} = \frac{205.9}{536.4} = 0.384\,\mathrm{STCm^3/kW}$$

where $Q_{\mathrm{GPU\,No.2}}$—generation of electric power, kW h,

With the power plant running in a combined mode (both electric and thermal power generation), the specific fuel consumption for the electric and thermal power in GPU 2 is equal to:

$$b_s = \frac{B}{\sum Q_{\mathrm{GPU\,No.2}}} = \frac{205.9}{536.4 + 780.2} = 0.156\,\mathrm{STCm^3/kW}$$

where $\sum Q_{\mathrm{GPU\,No.2}}$—generation of electric and thermal power, kW h,

- 536.4 kW h—electric power generated with GPU No. 2,
- 780.2 kW h—thermal power generated with GPU No. 2.

5 Conclusions

With the power plants running in combined mode (both electric and thermal power generation), the specific fuel consumption for the electric and thermal power generation in GPU 1, 2, 3 and 4 is equal to:

$$b_s = \frac{\sum B}{\sum Q_{\mathrm{GPU}}} = \frac{814.2}{(538.1 + 536.4 + 518.2 + 536.4) + 3068.6} = 0.157\,\mathrm{STCm}^3/\mathrm{kW}$$

where $\sum B$—natural gas consumed with GPU 1, 2, 3 and 4, STCm^3/h (predicted $(201.2 + 205.9) \times 2 = 814.2$); $\sum Q_{\mathrm{GPU}}$—electric and thermal power generation in GPU 1, 2, 3 and 4, kW h,

- 538.1; 536.4; 518.2; 536.4 kW h—electric power yield,
- 306.6 kW h—thermal power yield.

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