Pressurized Heat Recovery Steam Generator Design for CCGT with Gas Turbine GT-25PA and Steam Turbine T-100

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1 Introduction

There is a problem with existing steam-power unit reconstruction in Russia. The proposed solution of this problem is using the Pressurized Heat Recovery Steam Generator (PHRSG) in Gas Turbine Combined Cycle (CCGT) [1–3]. It will save a part of equipment—a steam turbine and regeneration system and it will save the costs. This technology will maximize the electrical efficiency of energy unit and give the electrical capacity growth. Finally, yet importantly, it meets the requirements of the Russian energy development program.

One of the ways of solving this problem is usage of pressurized heat exchangers. They are divided in two directions: steam generators for nuclear power plants (NPP) and pressurized boilers. The NPP steam generators were used gas coolant with high temperature (400–650 °C) and pressure (up to 55 bar). The flue gas pressure in pressurized boilers (pressurized steam generators—PSG) is less than 7 bar, but its temperature is higher comparing steam generators.

The technology of gas pressurized boilers is not new. It comes in the late 19th—early twentieth centuries. The first units [4] has low efficiency from 3 to 14% with a maximum coolant pressure of up to 4 bar and low reliability. Their technical and economic characteristics were limited by the level of used technologies: compression equipment, fitting (not welding) of tubes, low quality of construction materials. Similar installations were used mainly as ship power unit.

The technological capabilities improvement in the middle of the twentieth century gave a new opportunity to use the positive features of the pressurized coolant. There are the heat transfer intensification and the lower hydraulic resistance in new power plants: CCGT with PHRSG [4] and nuclear power plants with gas coolant [5, 6].

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There were also transport and process modifications of such installations and binary CCGTs with nuclear fuel usage [4].

The CCGT with PHRSG projects were limited by the level of used technologies. Thus, the operating experience of gas-cooled reactors (Magnox and AGR) has shown that the reactivity of CO_2 increases significantly at high temperatures [5–8]. Providing reliable operation, the outlet CO_2 temperature in operating reactors was reduced from 675–650 to 600 °C [5, 6, 8]. The steel with 9% of chromium content was required because of corrosion resistance demands. The other limitation for this technology development is difficulties with helium coolant application in NPP.

The key problem for CCGT with PHRSG development in thermal power engineering was lack of high-power gas turbines with high-temperature combustion products at the combustion chamber exhaust.

The development of new power equipment has several stages. In the first stage, a computational study and justification of technical and economic characteristics are carried out. This has been done successfully in previous studies [1, 2]. At the second stage of research, a study of the PHRSG thermal scheme and its individual elements was carried out [3]. The current stage of development involves design characteristics determination and design project development.

The main goal of the current stage project is to design the construction of the PHRSG. The tasks are materials selection, binding to the manufacturing technology, and scientific substantiation of the main technical solutions.

2 Power Plants Operating Under Pressure of Flue Gas

Significant experience in research and development of flue gas pressurized power plants has been accumulated. It includes boilers under low pressure of flue gas (less than 2 bar), common water-tube and fire-tube boilers [9–14], and plants with a pressure of combustion products from 4 to 20 bar used in different industries: circulating fluidized-bed (CFB) boilers [15–17], NPP steam generators [8, 18–21] and PHRSG for CCGT [4, 13, 22–24]. It can be divided in two categories: plants with a reactor and a cooler (PHRSG for CCGT, CFB boilers) and plants with only gas cooling (NPP steam generators).

Technical solutions of these plants have important features for high efficiency and reliability. The typical features of such plant reactors are as follows:

- furnace and burners must provide efficient, reliable, and environmentally friendly combustion;
- furnace has radiant membrane gas-tight water-cooled steel panels.

There are several typical features for cooling part of such plants:

- crossflow of heat-transfer tubes;
- finned tubes with external fins;

- air or water cooling of vessel or heat resistant alloys usage instead of thermal insulation;
- forced circulation for low-pressure and once-through tube system for high-pressure or supercritical boilers;
- several units in case of big capacity;
- polyhedral or cylindrical shape of vessel;
- rising direction of steam-water mixture flow.

It could have been possible to use not only existing PHRSG and fossil-fuel PSG design experience but also PSG for NPP groundwork for new type of PHRSG development. It can be made by analyzing the construction and operation characteristics of energy units for NPP (Table 1) and TPP (Table 2).

Table 1 describes the generalized data for different NPP units: Magnox—Berkeley, Bradwell, Hunterston A, Hinkley Point A, Trawsfynydd, Dungeness A, Sizewell A, Oldbury, Wulfa, Calder Hall [5, 24]. AGR—Dungeness B, Hinkley Point B, Hunterston B, Hartepool, Heysam, Torness [5–8, 19]. Project of Helical-coli steam generator for Next Generation Nuclear Plant (NGNP) was given in [21].

Table 1 Main characteristics of pressurized steam generators for nuclear power plant

Characteristic	Name		
	Magnox	AGR	NGNP
Inlet gas temperature, °C	340–415	600–650	750
Inlet gas pressure, bar	8–26	40	70
Vessel cooling	Not used	Not used	Not used
Vessel material	MnCrMoV/Ducol	Austenitic stainless steel 316	No data
Vessel thickness, mm	30–60	60–90	No data
Superheater material	No data	Austenitic stainless steel 316	Inconel 617/ Incoloy 800
Units amount	4–8	12	1
Superheater outlet steam temperature, °C	390	541	540
Superheater outlet steam pressure, bar	94	173	182
Steam flow rate, kg/s	No data	525	250
Type	Circulating/Once-through	Once-through	Once-through
Coolant	CO_2	CO_2	He

Table 2 Main characteristics of pressurized steam generators for fossil-fuel thermal power plant

Characteristic	Name			
	PHRSG-45	PHRSG-120	PHRSG-450	PHRSG-450
Furnace exhaust combustion products temperature, °C	1720	1700	1580	1780
Combustion products pressure, bar	3.7	4.8	6.5	6.5
Vessel cooling	Combustion air			
Units amount	1	1	2	2
Superheater outlet steam temperature, °C	440	540	570	538
Superheater outlet steam pressure, bar	39	98	137.2	241
Steam flow rate, kg/s	12.5	33.3	125	250
Type	Forced circulation	Forced circulation	Forced circulation	Once-through

Modern steam generators for NPP consist of one vessel [5, 6, 8]. PSG for TPP commonly consist of vessel with two shells. The internal dividing shell has cylindrical shape in furnace part and prismatic shape in convective part.

There is a conical transition between furnace part and the convective part from one shape to another. The internal shell contains heat exchange surfaces and provide combustion products flow. The external shell has cylindrical shape. It bears main weight and pressure stress. Combustion air flows between the internal dividing shell and the external shell. This technical solution provides the vessel cooling. It makes possible to use less expensive materials and to reduce both shells wall thickness [4, 22].

First PSG for NPP with gas coolant were used vessel with two shells also. New material development provided its reliable work with high temperature coolant and interaction with CO_2. It has given a possibility to remove the internal dividing shell from construction of vessel [8]. The simple access to tubes and headers was provided, but it also has increased the quantity of tube passes in vessel. Tubes were combined into groups of 3–4 tubes [5, 24] to reduce the amount of temperature compensators. All headers were located inside the vessel in once-through PSG [5–8, 19]. It has reduced the amount of passes in vessel considerable [8].

Finned tubes were used in first generation of Magnox reactors for NPP. Later the finning technology have become simpler and cheaper. New fin shapes appeared. This provided spreading of finning technology for different types of another heat exchangers. One linear meter of helically-finned tube with solid or serrated fins gives a heat transfer surface in 10–15 times greater than bare tube. Specific quantity of metal for bare tube (21.6 kg/m^2) in 5 times greater than for finned tube (4.86 $^{kg}/m^2$).

SG for NPP with helium coolant have broken the 650 °C barrier for the outlet temperature of CO_2 coolant. It has given a possibility to increase the reactor outlet parameters up to 730–950 °C with He pressure from 11 to 49 bar (less pressure corresponds grater temperature) [19]. The experimental UHTREX reactor showed that it is possible to obtain the reactor outlet coolant (helium) temperature up to 1320 °C [8, 25]. The increase of coolant temperature above the 1000 °C demands the nickel alloys application. Further SG for NPP development was limited by only technical and economic conditions.

The NGNP project has partially used the same design solutions as in previous generations. There are no insulation and vessel without cooling. To reduce the temperature and vessel wall thickness, helium in NGNP is located inside the tubes, and water is on the outside.

The vessel material in the NPP SG was chosen as the superheater material. It satisfied the highest operating temperature (Table 1). The vessel thickness was calculated for the coolant total internal pressure and temperature difference.

Due to the air cooling of the PSG vessel, it was possible to make it from carbon steel. Steel EI756 (12Cr11W2MoV) was used for primary superheater. Steel EI351 (10Cr2MoVNb) was used for secondary superheater. The estimated superheater metal temperature has not exceeded 630 °C.

3 PHRSG for CCGT with GT-25PA Gas Turbine

The design analysis of pressurized steam generators constructions has shown its typical technical solutions. This led to next design decisions for developing plant:

1. Vessel will be consisted of the internal dividing shell and external cylindrical shell. Shells will be cooled by exhaust flue gas after tail surface. This provides the less expensive steel usage and the shells wall thickness decrease.
2. The standard spacing for tubes will be used. It allows tubes finning.
3. The PHRSG heat transfer surfaces will be made of helically-finned tubes with serrated fins. It will reduce its capital cost.
4. The heat transfer surface headers will be located between two vessel shells. It will decrease the quantity of vessel passes and improve the PHRSG repairability.
5. PHRSG will be manufactured from standardized elements and separate blocks. These blocks will be shop-assembled.

The operational parameters choice, methodic description, and ways of thermal calculations were described in [1–3]. Key calculations were carried out with Boiler Designer [26–29] and Ansys [30–32] software. These programs have shown reliable results, and they are widely used in energy research and development sector.

The designed energy unit parameters are shown in Table 3. This plant works with

Table 3 Main characteristics of one PHRSG

Characteristic	Power unit
Inlet flue gas temperature, °C	787.6
Inlet flue gas pressure, bar	4.5
Inlet flue gas mass flow, kg/s	155
Vessel cooling	PHRSG exhaust combustion products
Vessel material	Steel 20
Vessel thick, mm	15
Units number	4
Superheater steam outlet temperature, °C	560
Superheater steam outlet pressure, bar	138
Superheated steam mass flow, kg/s	36.7
Exhaust flue gas temperature, °C	274

T-100 steam turbine. It consists of 4 units. Each unit consists of two GT-25PA gas turbines and one PHRSG. Total superheated steam mass flow equals 146.8 kg/s.

Main PHRSG construction characteristics are shown in Table 4. The results of its thermal calculation are shown in Table 5.

The construction of PHRSG is shown in Fig. 1. Flue gas comes to PHRSG and passes surfaces. The surfaces are located inside the internal dividing shell. This shell has quadratic shape with side length of 3.1 m. The flue gas passes superheater 2, superheater 1, evaporator, and economizer. After economizer the flue gas comes to annular gap between two vessel shells: internal and external. Flue gas leaves the PHRSG after cooling the internal shell.

Materials and tubes were taken from standard assortment. These materials are produced by Russian industry (Chelyabinsk Pipe Plant; Pervouralsk Pipe Plant, etc.). High-alloy steels for superheaters will be produced by special order. Tube spacing and fins parameters were taken according to HRSG manufacturing experience by JSC «Machine-Building Factory of Podolsk» (JSC «ZiO»).

The economizer and the superheater are made of counterflow scheme. The evaporator is designed with parallel flow scheme. This was made to increase the operation reliability.

The inlet part of PHRSG is made of 08Cr17H13Mo2Ti (factory code—EI756, analogue of 316H) alloy steel. Alloy steel EI914 (08Cr18H10Ti or 08Cr18Ni10Ti) is used for the internal dividing shell in the region with temperature less than 700 °C (after superheater 1). This shell is made of carbon steel 20 after evaporator.

Table 4 Main heat-transfer surfaces characteristics

Characteristic	Heat surface			
	Super-heater 2	Super-heater 1	Evapo-rator	Econo-mizer
Material	EI756	12Cr1MoV	Steel 20	
Heat surface, m^2	259.3	259.3	2853.8	4566.1
External tube diameter, mm	32	32	38	38
Tube wall thickness, mm	5	5	4	4
Number of parallel tubes	104	104	760	76
In-line spacing, mm	60	60	80	80
Longitudinal spacing, mm	55	55	70	70
Number of tube rows	18	12	24	30
Heat surface height, mm	935	605	1610	2030
Gas flow cross-sectional area in last row, m^2	4.45	4.45	4.27	4.27
Medium flow cross-section area in tubes, m^2	0.118	0.118	0.107	0.161
Fin height, mm	–	–	15	15
Fin thickness, mm	–	–	1	1
Fin spacing, mm	–	–	4.1	4.1
Tube mass, kg	8532	8532	7852	12.6
Fin mass, kg	–	–	8026	12.8
Total mass, kg	8532	8532	15.9	25.4

Table 5 The PHRSG thermal calculation results for CCGT with GT-25PA gas turbine and T-100 steam turbine

Characteristic	Heat surface			
	Super-heater 2	Super-heater 1	Evapo-rator	Econo-mizer
Gas velocity, m/s	18.86	17.28	15.01	11.83
Heat capacity, MW	15.6	17.0	40.0	19.3
Inlet gas temperature, °C	788	704	612	387
Exhaust gas temperature, °C	704	612	387	274
Water/steam velocity, m/s	20.24	13.52	2.34	0.95
Water/steam enthalpy difference, kJ/kg	425.78	471.5	59.78	516.55
Inlet water/steam temperature, °C	417	339	338	232
Exhaust water/steam temperature, °C	560	428	339	330
Overall heat transfer coefficient, $W/m^2 \cdot °C$	232	231	108	91
Temperature difference, °C	259	283	130	46

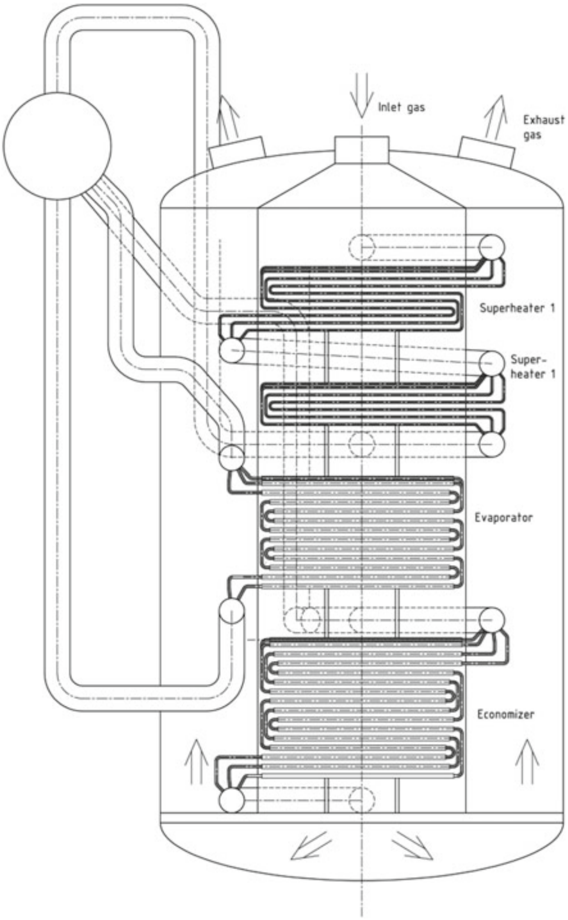

Fig. 1 PHRSG longitudinal section

4 Further Investigations

Further design development consists of natural circulation calculating and technical solutions substantiating for evaporator reliable operation. It could have been possible to organize natural circulation or multiplied forced circulation. Recent developments have shown that natural circulation can be used in horizontal tube evaporators [10, 28, 33].

The calculating of internal dividing shell wall temperature gives information about choosing less expensive materials for its production.

The water/steam enthalpy increase in PHRSG is much larger than in common energy boilers [26, 34]. However, there is no furnace in the PHRSG, and its construction is simpler. The flue gas density and flue gas flow steadiness are much higher. According to initial estimates, it is possible to simplify the design of heat exchange surfaces. The final decision can be made only after thermal and hydraulic calculation of the heat transfer tubes in surfaces.

5 Conclusion

1. The analysis results of the SG for NPP with a gas coolant and old constructions of PHRSG made it possible to use its experience and technical solutions in the design of new PHRSG.
2. Cooling the vessel by flue gas allows the use of carbon steel. It reduces the use of expensive austenitic alloy steel.
3. The development and manufacturing of PHRSG can be carried out by enterprises of the power engineering industry in Russia.

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