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Use of heat pumps in turbogenerator hydrogen cooling systems at thermal power plant☆

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ABSTRACT

The possible increase in heat power generation efficiency was evaluated through this paper via installation of heat pumps for cooling hydrogen in generator of steam turbine.

Using the heat pumps, the biggest part of waste heat from turbogenerator hydrogen cooling systems can be transferred to heat supply system. They are used for heat supply in-house load of a power plant or for any other goal of heat supply as well.

All calculations were made for thermal power plant at the branch "Nevsky" "TGC-1" company – CHP-21. The analysis was made for heat pumps with heat capacities of 2 MW and 3 MW. The application of such analysis on CHP was applied by the method of detailed settlement estimation of the impact on CHP operating mode with synchronous calculation of characteristics of heat pump. The analysis was made for different operating mode of CHP. A low potential heat source is the water from hydrogen cooling systems of steam turbine generator.

The use of heat pumps for steam turbine generator hydrogen cooling system waste heat salvaging is innovation solution to increase TPP cost-performance ratio. On implementing cycle arrangement with heat pump used for sanitary and service makeup water warming, fuel saving is up to 700 toe/year while heat pump system specified heat power is 3 MW.

Introduction

Strategic target of Russian state energy policy is the utmost rational use of energy resources, based on consumers' concern in energy saving, in proper energy efficiency increase and in investing into this sector [1].

On using primary fuel cells in technological cycle, thermal power plants (TPP) have large stock of reclaimable resources which are little used, and they also have a negative impact on the environment. Heat output from turbogenerator hydrogen cooling system should be considered as such resource. One of the possible solutions to the problem of turbogenerator hydrogen cooling system's closed-loop system heat saving is the use of heat pumps (HP).

The use of HP at TPP could have the following effects:

- to save low grade heat;

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Nomenclature

G	consumption, t/h
h	heat content, kJ/kg
Q	heat production, MW
t	temperature, °C

Greek letters

χ	steam dryness factor

Superscripts and subscripts

CBC	continuous blowdown coolants
CBF	continuous blowdown flash tank
RWW	raw water warmers
WT	water treatment
bw	blowdown water
in	inlet
out	outlet
rw	raw water
s	parameters in saturation line at pressure in CBF
st	steam
ww	warming water
w	water

Acronyms/abbreviations

ARR	Average rate of return
BIB	built-in bundle of condenser
CAD	computer-aided design
CBC	continuous blowdown coolants
CBF	continuous blowdown flash tank
CHP	combined heat and power plant
CPR	cost-performance ratio
DPB	Discounted payback period
EFSF	equivalent fuel specific flow
goe	gram of coal equivalent
HP	heat pump
HPS	heat pumping system
IRR	Internal rate of return
JSC	Open Joint Stock Company
LGHS	low-grade heat source
MW	megawatt
NPV	Net present value
PB	Payback period
PI	Profitability index
Ps	saturated pressure
Q_{HPS}	HPS specified heat power
Q_{RWW}	RWW thermal load value
RD	regulatory document
RWW	raw water warmers
TGC	Territorial Generating Company
TPP	thermal power plant
toe	ton of coal equivalent
TVF	type turbogenerators with hydrogen cooling
WEM	wholesale electric energy/power market
WT	water treatment

- to improve TPP environmental factors;
- to provide in part or total TPP auxiliary heat requirements;
- to increase heat supply;
- to decrease firing rate (by peaking hot water heater load decrease);
- to increase TPP output power (by steam turbine heat extraction load decreases) [2,3];
- to decrease technological minimum value of steam turbine plant.

Several HP arranged as heat pumping system (HPS) could be used to increase reclaimable resources' saving adjustment range.

Research technique

Performance analysis of HPS use in TPP cycle arrangement has been carried out by means of detailed assessment calculation of the system effect on TPP operating mode. At the same time energy efficiency rate, as well as approximate consumption for compressor drive in various TPP operating modes required for heat and electricity supply has been calculated.

Elementary scheme of one-stage heat pump, operating on Freon R134a which is widely used and is considered to be ozone-friendly coolant, has been selected for analytical model. CoolPack software has been used to evaluate the heat pump performance. Working fluid (or working medium) of vapor compression heat pump should meet the following requirements:

1. It should have high heat capacity and high density.
2. It should have stay-put feature and low cost [4].

In order to decrease compression work, it is necessary to fulfill the following conditions: working medium saturated pressure (P_s) in evaporator should be close to atmospheric pressure; working medium saturated pressure (P_s) in capacitor shouldn't be too high. The selection of heat pump elementary scheme is caused by the fact that it is the least favorable modification with ultimate consumption for compressor drive. So, one may conclude in accordance with this modification calculation that engineering development of the scheme could improve heat pump thermodynamic cycle and decrease thereafter consumption for compressor drive.

Statistical data along with cycle arrangement mathematical model approach has been used to evaluate reclaimable resources effect on TPP operating modes and to estimate its key technical-and-economic indexes. Russian United Cycle software has been used to develop mathematical models. United Cycle package is a new version of "Cycle arrangement" CAD system and is designed for solving problems of heat and power facility optimal structure and configuration, as well as for calculating of TPP steady states of operation [5].

Subject of research

Thermal power plant of Severnaya CHHP JSC TGC-1has been selected for HPS performance analysis in operating TPP. Five turbine generators TVF-120-2UZ have been installed at TPP. The TVF-type turbogenerators with hydrogen cooling have direct forced hydrogen cooling of rotor winding and indirect hydrogen cooling of stator winding. Hydrogen is cooled by gas condensers, embedded in stator frame horizontally.

Cooling water is delivered to gas condenser system by special supercharger pumps, connected to input pipelines of turbine capacitors. Each turbine is provided by two supercharger pumps (operating and stand-by). Heated water from hydromechanical systems collects in recycled water outlet pipeline-Ø800 mm and flows directly into cooling tower cups passing spraying device by, and thus warming up water cooled in cooling towers.

Circuitry

Outlet water of gas condensers, used in steam turbine generator hydrogen cooling system, is HPS low-grade heat source (LGHS). LGHS has the following points in its favor:

- LGHS has high heat-transfer coefficient;
- no outer air temperature effect;
- cooling water goodness increases HP life;
- no extra capital costs for LGHS intake and transportation.

LGHS demerits are:

- direct intercoupling with generator performance;
- critical hydrogen temperature span maintenance is essential.

Gas condenser inlet hydrogen specified temperature is 60 °C, while outlet temperature is 40 °C, nominal value of one generator gas condenser outlet discharge is 360 m^3/h, and gas condenser inlet water rated temperature is 33 °C. Estimated value of water heat output, used in steam turbine generator hydrogen cooling system, has shown that LGHS voltage varies within the range from 16.7 MW to 41.9 MW. While selecting heat consumers, two modifications of HPS arrangement have been considered. First modification is to use HPS at TPP-21 for raw water warming before water treatment (WT). It is suggested that HPS has been arranged next to continuous blowdown coolants (CBC) as a substitute for raw water warmers (RWW). This solution would allow decreasing losses, caused by use of system water heat in raw water warming [6,7]. Second modification is to warm heating system makeup water and makeup for sanitary and service water. HPS is suggested to be arranged past internal capacitor assembly (ICA) of three power-generating blocs (№1, №3, and №5) directly.

HPS specified heat power (Q_{HPS}) for raw water warming before WT is determined by RWW thermal load value (Q_{RWW}) and by TPP operating mode.

RWW thermal load value has been calculated from Formula:

$$Q_{RWW} = G_{rw}^{WT} \cdot \left(t_{rw\_in}^{WT} - t_{rw\_out}^{CBC} \right) \cdot 1.163$$

Due to the lack of statistical data, CBC outlet raw water temperature has been calculated according to the following Formula:

$$t_{rw\_out}^{CBC} = \frac{G_{bw\_out}^{CBF} \cdot \left(t_{bw\_out}^{CBF} - t_{bw\_out}^{CBC} \right)}{G_{rw}^{WT}} + t_{rw\_in}^{CBC}$$

Blowdown water flow has been calculated by the Formula:

$$G_{bw\_out}^{CBF} = G_{bw} - \frac{G_{bw} \cdot \left(h_{bw} - h_{w\_CBF}^{s} \right)}{\chi_{out}^{CBF} \cdot \left(h_{st\_CBF}^{s} - h_{w\_CBF}^{s} \right)}$$

The calculations have shown that raw water average temperature at CBF outlet varies in the course of a year in the range from 18 °C to 20 °C. RWW heat power is 0.64 MW in summer mode and is 2 MW in winter mode. Therefore, four parallel HP with unit capacity of 0.5 MW are suggested to be arranged. Total heat power of HPS would be 2 MW. HP is suggested to be installed in boiler room next to CBC. HP cycle arrangement for raw water warming is shown in Fig. 1 (circuitry №1).

Possibility of heat pump arrangement directly after internal capacitor assembly (ICA) has been considered as second modification of HPS use for warming heating system makeup water, as well as for sanitary and household needs. It must be borne in mind that nowadays Saint-Petersburg municipal open heat supply system is changed stepwise into closed heat supply system, which could result in makeup water flow reduction. Yet makeup water flow complete minimization couldn't be achieved in the short run due to loss of coolant in heat supply system, as well as to necessity for providing makeup water flow for sanitary and household needs. Thus, heat pump arrangement past turbine internal capacitor assembly could be a cost-effective solution within the next 20–30 years.

Analysis of historical data on TPP-21 performance has shown that it's possible to arrange HP past internal capacitor assembly (ICA) of three power-generating blocks (№1, №3, and №5). The decision derives from the fact that water flow through ICA of these power-generating blocks is higher than of others (power-generating blocks №2, and №4). Moreover, capacitor assembly construction design at power-generating blocks №1, №3, and №5 provides two water moving streams through internal capacitor assembly, while it provides four water moving streams in power-generating blocks №2 and №4. Therefore, average temperature outside ICA of power-generating blocks №1, №3, and №5 is lower than of power-generating blocks №2 and №4, being within the range of 20–25 °C. It is suggested that one HP having a capacity of 1 MW should be arranged at each power-generating block (HPS total heat power is 3 MW). Fig. 2 (circuitry №2) shows flow sheet of one power-generating block.

Calculation of HPS effect on TPP cost-performance ratio

In order to estimate HPS effect on TPP cost-performance ratio (CPR), calculation of equivalent fuel specific flow (EFSF) needed for power generation and heat supply has been carried out for four typical TPP-21 operating modes:

- winter mode (I) with heavy heating loads, five operating power-generating blocs;
- winter mode (II) with light loads, three operating power-generating blocs;

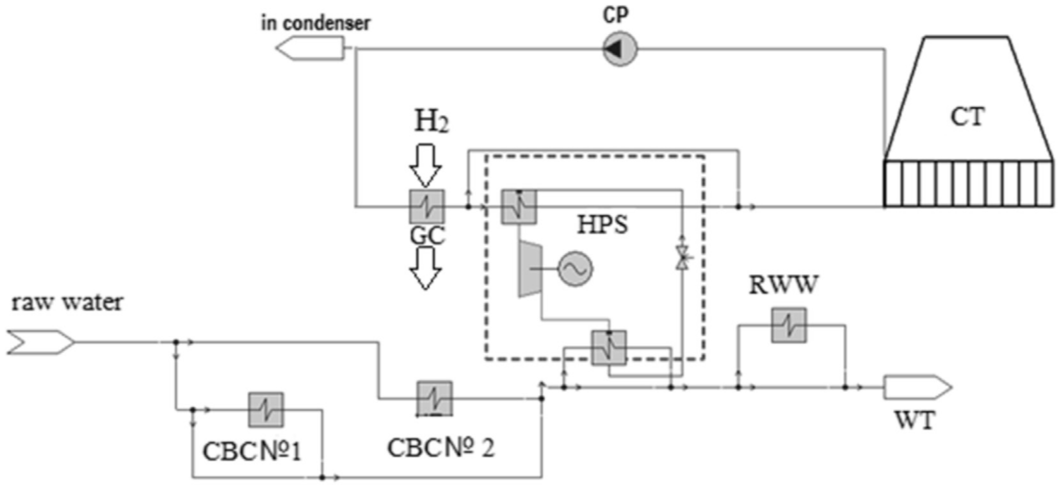

Fig. 1 – HP cycle arrangement for raw water warming before water treatment and for TPP-21 turbogenerator hydrogen cooling systems heat salvaging. (CP is circulation pump; GC is turbogenerator hydrogen cooling system gas condenser; CT is cooling tower; HPS is heat pumping system; CBC is continuous blowdown coolant; RWW is raw water warmer; WT is water treatment).

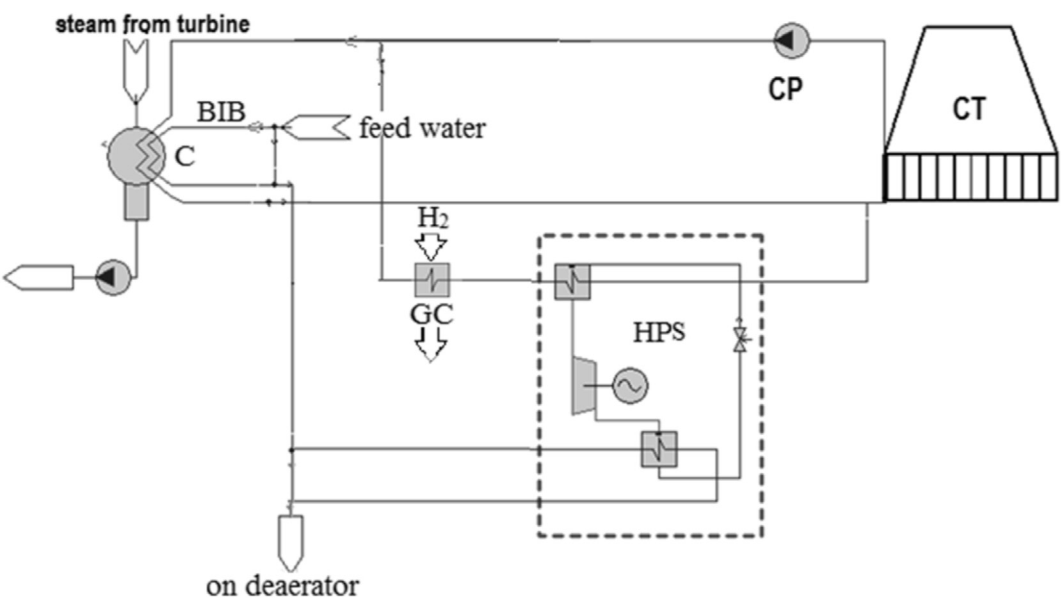

Fig. 2 – HP cycle arrangement for sanitary and service water makeup warming and TPP-21 turbogenerator hydrogen cooling systems heat saving. (CP is circulation pump; CT is cooling tower; C is steam-turbine condenser; BIB is built-in bundle of condenser; GC is turbogenerator hydrogen cooling system gas condenser; HPS is heat pumping system).

- periodic heating mode (III), two operating power-generating blocs;
- summer mode (IV), two operating power-generating blocs.

Calculation of equivalent fuel specific flow (EFSF) needed for power generation and heat supply has been carried out in accordance with Standard RD 34.08.552-95 "Methodical guidelines for preparation of equipment heat efficiency report of power plant and power engineering and electrification joint stock company" [8].

Calculation of fuel specific flow estimated result (Table 2) has been carried out for two cycle arrangements (Figs. 1 and 2), two versions of each cycle arrangement have been considered – with HPS (projectable arrangement) and without HPS (actual arrangement) (Fig. 3). Decrease of actual equivalent fuel specific flow (EFSF) needed for power generation is 0.1 goe/kW h in HPS cycle arrangement №1 at modes I and II, and in HPS cycle arrangement №2 at mode I (Fig. 3a). HPS doesn't effect EFSF needed for power generation at other modes under study. Actual EFSF, needed for heat supply has been decreased by 0.086 goe/kW h in HPS cycle arrangement №1 and by 0.17 goe/kW h in HPS cycle arrangement №2 at modes I and II. Decrease of EFSF needed for heat supply at other modes under study is 0.17 goe/kW h for cycle

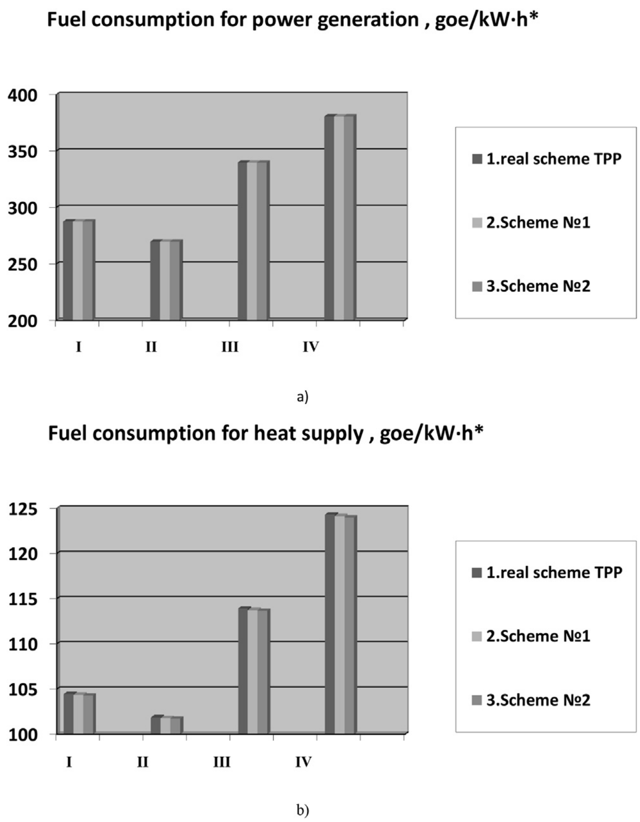

Fig. 3 – Equivalent fuel specific flow needed for a) power generation, b) heat supply. * – the fuel with combustion value 29,3 MJ/kg 1. Cycle arrangement without HPS (real scheme TPP); 2. Cycle arrangement with HPS used for raw water warming before WT (projectable arrangement – scheme №1); 3. Cycle arrangement with HPS used for sanitary and service makeup water warming (projectable arrangement – scheme №2).

arrangement №1 and is 0.26 goe/kW h for cycle arrangement №2 (Fig. 3b).

Analysis of results

In considering a number of factors, circulating water heat after steam-turbine condenser is suggested to be used as LGHS. Cycle arrangement mathematical model calculation analysis has shown that HPS doesn't effect significantly fuel specific flow needed for power generation, while it does effect fuel specific flow needed for heat supply. Maximum effect of 0.34 g/kW h (cycle arrangement №2) could be achieved by HPS, used for service makeup water warming in summer mode (IV). Given that TPP running time in periodic heating mode (III) is less than 1 per cent of TPP operating life, equivalent fuel annual saving calculation has been carried out only at three TPP operating modes in estimating HPS efficiency (Table 1).

Calculation analysis has shown that the best economic results could be achieved by cycle arrangement №2 implementation. Thus, expected fuel saving could be up to 700 toe per year. Given that HPS installed capacities are not equal in value, cost estimate with allowance for financial cost component connected with HPS installation should be carried out in estimating modifications comparability.

Economic analysis of effectiveness indices dynamics of TPP with heat pumps

Estimation of modifications comparability has been carried out under condition of HPS year-round operating mode with the following initial data (Table 2):

1. Maximum operating time is 8760 h/year;
2. Maximum operating time at mode (I) is 708 h;
3. Maximum operating time at mode (II) is 4532 h;
4. Maximum operating time in summer mode (IV) is 3520 h.

Tentative investment value assessment has been carried out, which includes HPS price and mounting costs, HPS coolant delivery system price and mounting costs, and also pumping equipment price and mounting costs. It is suggested that the project would be financed with its own funds as loan funds require high costs [9]. Generation and sale of electricity and heat power program calculation, as well as fuel costs along with key performance indicators calculations of TPP with heat pumps have been carried out in accordance with TGC-1 JSC operating results on wholesale electric energy/power market (WEM) for 2015. Calculation results are shown in Table 3. HPS operating life at TPP has been considered to be 15 years. On studying the results, it is suggested to install HPS with a capacity of 3 MW (cycle arrangement №2) at TPP-21. Estimated payback period of the project is 8.5 years. Fuel saving for this period will be about 5600 toe.

Basic risks for implementation of this engineering solution are the following:

1) Changes in price growth rate on WEM;
2) Changes in heat tariffs growth rate;

Table 1 – Equivalent fuel annual saving due to HPS.

Mode №	Cycle arrangement №1 (HPS capacity is 2 MW)			Cycle arrangement №2 (HPS capacity is 3 MW)		
	Mode time, h	Q from HPS, MW	Fuel saving, toe/year	Mode time, h	Q from HPS, MW	Fuel saving, toe/year
I	708	2.0	66.9	708	3.0	99.3
II	4532	1.16	252.5	4532	2.0	432.3
IV	3520	0.64	108.4	3520	1.0	168.3
Total per year	8760	8946.71	427.8	8760	14710.65	699.9

Table 2 – Initial data for calculation of heat pumps economic efficiency at TPP-21.

Value	Unit Measure	Without HPS	Cycle arrangement №1	Cycle arrangement №2
Heat supply	thou. MW h	2942.2	2951.1	2956.8
Power generation	mil. kW h	1606.4	1606.4	1606.4
Auxiliary power consumption	mil. kW h	208.6	210.4	211.6
Fuel flow needed for power generation	thou. toe	415.9	415.4	415.1
Fuel flow needed for heat generation	thou. toe	312.4	313.0	313.3
EFSF needed for power generation	g/kW h	297.59	297.57	297.58
EFSF needed for heat supply	g/kW h	123.50	123.35	123.24

Table 3 – Cost-effectiveness analysis of HPS at TTP-21.

Value	Cycle arrangement №1	Cycle arrangement №2
Investment, mil. Rbl.	50.3	54.4
Payback period (PB), years	More than 15 years	8.5
Discounted payback period (DPB),years	More than 15 years	11.1
Net present value (NPV), mil. Rbl.	–	9.3
Internal rate of return (IRR), %	–	0.18
Profitability index (PI)	–	1.17
Average rate of return (ARR)	–	0.12

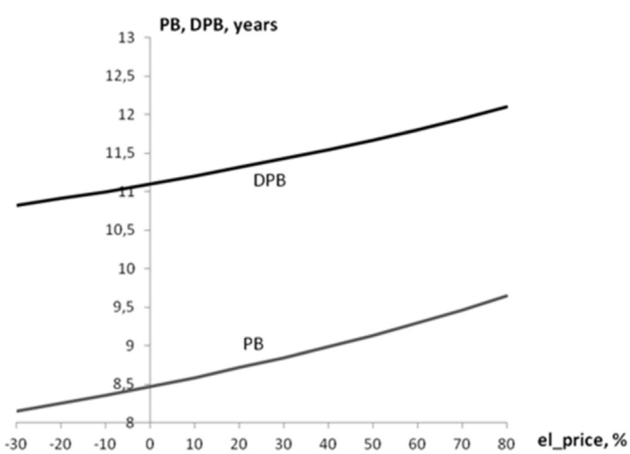

Fig. 4 – Analysis of project sensitivity to changes in electricity price growth rate on wholesale electric energy/power market (el_price).

3) Changes in fuel price growth rate;
4) Capital costs increase.

Potential risk assessment in implementing energy-saving measures with HPS used in cycle arrangement №2 has shown that the project wouldn't be paid back if capital costs increases at more than 19%.

30% slowdown of price growth rate on WEM would shorten payback period (PB) by 5%, and discounted payback period (DPB) by 3%; 80% increase of growth rate would result in these values increase of 12% and 8% respectively (Fig. 4).

Conclusion

1. Analysis of the results has shown that use of HPS for steam turbine generator hydrogen cooling system waste heat saving is innovation solution to increase TPP cost-performance ratio.
2. Comparative analysis of HPS cycle arrangements at Severnaya TPP-21 has shown that use of HPS for raw water warming (Fig. 1) before water treatment is economically inadvisable.
3. On implementing cycle arrangement with HPS used for sanitary and service makeup water warming, fuel saving is up to 700 toe/year while HPS specified heat power is 3 MW.
4. The arrangement payback period of the project is 8.5 years, NPV is 11.9 million roubles.
5. Sensitivity analysis has shown that if capital costs increase by 19%, the project wouldn't be paid back.

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