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Energy saving during the partial heat load period by integrating a steam-heated absorption heat pump into the thermal scheme of a PT-60/70-130/13 steam turbine

Aleksandr Shubenko[1],

Mikola Babak[2],

Aleksandr Senetskyi[3],

Yana Forkun[4]

[1] *Anatolii Pidhornyi Institute*
of Mechanical Engineering Problems
of the National Academy of Sciences of Ukraine,
vul. Pozharskog, 2/10, Kharkiv 61046, Ukraine
Email: shuben@ipmach.kharkov.ua

[2] *Anatolii Pidhornyi Institute*
of Mechanical Engineering Problems
of the National Academy of Sciences of Ukraine,
vul. Pozharskogo 2/10, Kharkiv 61046, Ukraine
Email: babak@ipmach.kharkov.ua

[3] *Anatolii Pidhornyi Institute*
of Mechanical Engineering Problems
of the National Academy of Sciences of Ukraine,
vul. Pozharskogo 2/10, Kharkiv 61046, Ukraine
Email: senetskyi@ipmach.kharkov.ua

[4] *O. M. Beketov National University*
of Urban Economy in Kharkiv,
17 Marshal Bazhanov Street,
Kharkiv 61002, Ukraine
Email: jana.forkun@gmail.com

The task of determining the efficiency of operation of an absorption heat pump (AHP) with steam heating (COP conversion factor = 1.71) integrated into the thermal circuit of a PT-60/70-130/13 steam turbine that releases production steam and hot water during the partial heat load period (spring and autumn; also referred to as the inteheating period) is being solved in this paper. Variants of operation of the PT-60/70-130/13 with an integrated AHP with a capacity of ~17.25 MW in the partial heat load period were studied when steam with parameters of 1.296 MPa, 280°C was realised in the production selection of the adjustable turbine at flow rates of 20, 30, and 50 t/h with a variable heat load on hot water supply, which was determined by the return network water consumption task 1000–1400 t/h, while the 'useful' electrical power of the power complex was provided at ~30 MW. At electricity prices of 0.13 USD/(kWh) and standard fuel of 309 USD/t for Ukraine, the simple payback period of 17.25 MW AHP as part of the PT-60/70-130/13 steam turbine for the partial heat load period at a production load of 20–50 t/h of steam at the consumption of return network water of heat supply 1000–1200 t/h can decrease to two years. At the same time, during the partial heat load period, which lasts ~4404 hours in Ukraine, up to ~1.2% of fuel, up to 44% of technical water for feeding the circulation cooling system, and 0.4% of softened water for feeding are saved. A tangible environmental effect is achieved due to the reduction of harmful emissions – actual heat and hazardous gases – to the atmosphere: CO_2 by 1118.7 tons, NO_x by 5.87 t, thus saving ~41,000 of technical water.

Keywords: energy saving, steam turbine, absorption heat pump, hot water supply, partial heat load period

INTRODUCTION

The turbine generator of a power plant has several heat flows: flue gases, condenser (steam turbine) cooling water, generator, and lubrication system, which are dissipated in the environment. Thus, for the PT-60/70-130/13 (PT-60) steam turbine at rated load in the heating mode, the power of water flow when cooling the condenser $Q_{\mathrm{p\ c}}$ is ~6.3 Gcal/h (steam flow ~12 t/h), the total power of the lubricant cooling systems (LCS) and generator (GCS) $Q_{\mathrm{LCS+GCS}}$ ~0.47 MW [1]. As a result, Q_{Σ} ~6.77 Gcal/h of heat is released into the atmosphere in the cooling tower.

A modern energy-saving approach to recycling Q_{Σ} is integration of the absorption heat pump (AHP) into the power plant thermal scheme (TS). Corresponding projects have been implemented in many leading countries, which provides certain economic benefits [2]. In China, the requirement to implement AHP during the construction of thermal power plants is defined at the legislative level when implementing projects, for example [3, 4].

The energy-saving issues of the integration of a AHP with steam heating into the TS of steam turbines are covered in [1, 3–9] and others.

The simplest AHP with steam heating with one-stage regeneration (or step-down thermo-transformer) combines four heat exchangers placed in one integrated housing. Two heat exchangers (generator and condenser) work at higher pressure; their purpose is to quickly obtain boiling liquid (water); two-second heat exchangers (evaporator and absorber), at reduced pressure, remove thermal energy from the source and turn the resulting vapour into a liquid solution component [10].

AHP efficiency is evaluated by the coefficient of performance μ (or COP), which is determined

$$\mathrm{COP} = Q_{\mathrm{AHP}} / Q_{\mathrm{h}},$$

where Q_{AHP} – the amount of heat removed from the AHP (useful), Q_{h} – the amount of heat supplied from an external source.

The main advantages of ANP [10]:

– the source of heating heat, such as process liquids, gases, water vapour, and heated coolant can be any source with a temperature up to +60°C;

– relatively expensive and harmful ammonia and freons are not used;

– high reliability (no moving parts), no vibration or noise;

– longer service life than in vapour-compression heat pump unit (HPU) at lower costs.

The main disadvantages of AHP:

– operation frequency (additional energy consumption for heating/cooling both the sorbent and the adsorber body);

– relatively low parameters of heat flow from HPU (up to +90°C), and, as a consequence, a lower efficiency level;

– high metal consumption (some of the heat exchangers are under vacuum) and, as a consequence, high capital costs.

When researching the integration of AHP into the technical structure of turbine units (TU), insufficient attention was paid to determining the efficiency of HPU functioning during the partial heat load period (spring and autumn), which is what prompted this work.

The results of computational studies of PT-60 TS with integrated AHP when operating during the partial heat load period should be added to the previously obtained results with HPU integrated for the heating period.

An analysis of the problem state has shown that powerful 'T' and 'PT' turbines [11] operating with a large thermal load (in frost conditions, the peak hot water boiler (PHWB) is turned on to the heat generation, and TU operates with a fixed electrical power, which is favourable for HPU).

For Ukraine conditions, these are steam turbines PT-60/70-130/13 (three units) and T-110/120-130 (eight units), which are quite powerful and are available at combined heat and power plants (CHPP). In this work, the PT-60 turbine was chosen as the object of AHP integration as the most widely produced among those manufactured in Soviet times (over 390 turbines of this type were produced). Therefore, the selection of the type of the turbine was based on the following factors:

– quantity in the world;

– electrical and thermal power;

– functioning during both the heating and partial heat load periods;

– the results can be applied to similar power plants from other.

The current service life of installations of this type is very different. According to available data from global manufacturers, they regularly reconstruct and modernise existing power plants in order to increase efficiency with minimal changes to supporting structures. Therefore, the results obtained are relevant at the moment and will be relevant for decades to come for countries that rely on semi-peak and base-load energy.

The PT-60 steam turbine with a condensing unit and two adjustable steam extractions is a two-cylinder single-shaft unit. It has high- and low-pressure cylinders; the latter includes parts: medium and low-pressure (MPP and LPP, respectively).

PT-60 has seven steam extractions, three high-pressure heaters (HPH), and four low-pressure heaters (LPH). Its main characteristics are given in Table 1 [12].

The minimum steam passage into the LPP with a closed rotary control diaphragm (RCD) is ~12 t/h with an airtight diaphragm. In Ukraine, the PT-60 is Soviet-made, their RCD is not airtight, and the steam consumption in LPP G_k > 24 t/h (idling steam flow rate [12]).

A mathematical model was developed to carry out computational studies. It allowed carrying out calculations depending on the initial characteristics of the installation. The specified parameters are the initial data for this turbine and are specified in the mathematical model. The initial data can be changed, and the flow rate characteristics, efficiency indicators, etc. will change accordingly. But since in most cases such and more powerful installations are designed to operate in nominal mode, their efficiency at partial load will accordingly decrease.

As for the calculation of installations of another type, it can be performed by specifying the appropriate initial data.

COMPUTATIONAL RESEARCH METHODOLOGY

Mathematical model of AHP

In general, modelling heat exchange processes in AHP is difficult since TNU includes heat exchangers where absorption-desorption processes occur, and knowledge of the characteristics of each machine element, thermodynamic properties of heat carriers, and their flow rates is required [10].

AHP works with three energy flows:

– water steam with flow rate G_h, which heats the HPU (taken from the extraction of the turbine, in the case of PT-60 from the industrial production), with initial parameters: pressure P_{h1} 0.14–0.6 MPa, temperature t_{h1} 110–150°C;

– technical water with G_s flow rate and initial temperature t_{s1} +7–35°C, the heat of which is recovered (circulating water (CW)) of the condenser cooling systems, LCS and GCS;

– water with G_w flow rate and initial temperature of the heated water t_{w1} (return network water (RNW), possibly make-up water).

To model the AHP indicators, the following were used: performance curves of HPU of the Broad Corporation (Fig. 1), SKB 'Teplosibmash' nomograms (. 2), and their general characteristics (Table 2).

Nominal parameters of heat carriers:

– water temperature, inlet/outlet: t_{s1}/t_{s2}, 30/25°C ($\Delta t_s = 5$°C); t_{w1}/t_{w2}, 50/80°C;

– heating steam pressure $P_{h1} = 0.5$ MPa (abs).

Table 1. **Characteristics of powerful AHP with steam heating according to a single-stage regeneration scheme of the Broad Corporation brand BDS [3]. COP = 1.71, $\Delta t_w = t_{w2} - t_{w1} = 30$°C**

	Parameter	Unit	Value
1	Turbine nominal power	MW	60
2	number of rotations	rpm	3000
3	fresh steam parameters before the stop valve: – pressure (P_0) – temperature (T_0)	MPa °C	12.75 565
4	Steam pressure of regulated extractions: – industrial production (P_{ip}) – heating (P_h)	MPa MPa	0.686–1.666 0.0294–0.147

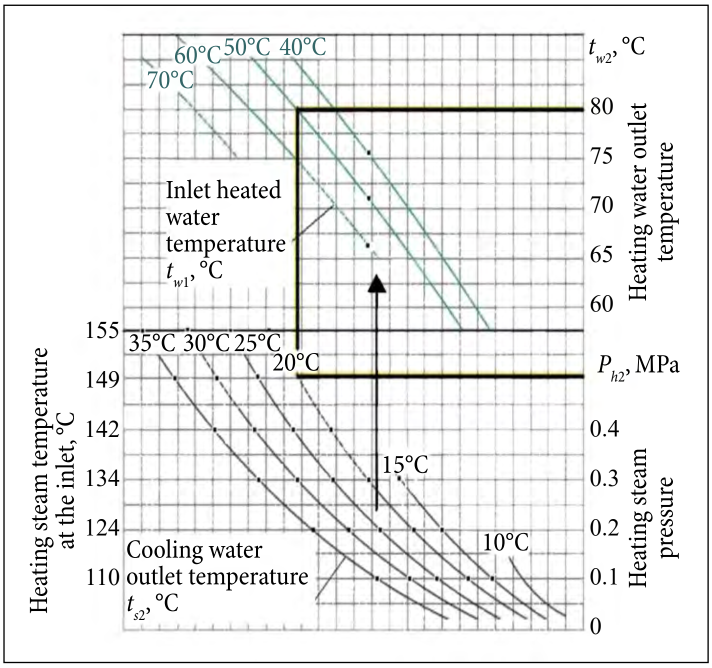

Fig. 1. Performance curves of Broad Corporation AHP showing the pump parameters [3]: ▬▬ – AHP is heated by steam with standard parameters: 0.5 MPa, 149°C

For each of steam pressures P_{h1} (Fig. 1), which are heating HPU, t_{w2} were determined for known temperatures: the cooled CW at the outlet of HPU t_{s2} and the heated RNW at the inlet to HPU t_{w1}. The latter table is the basis of the interpolation algorithm that implements the dependence

$$t_{w2}(P_{h1}, t_{s2}, t_{w1}). \tag{1}$$

The table of base point values of straight lines on nomograms in Fig. 2 is the basis of the algorithm that implements the dependence

$$\bar{Q}_{AHP}(t_{w1}, t_{w2}, t_{s2}). \tag{2}$$

Using data on the characteristics of AHP of the Broad Corporation (Table 2), approximation expressions were constructed to determine:

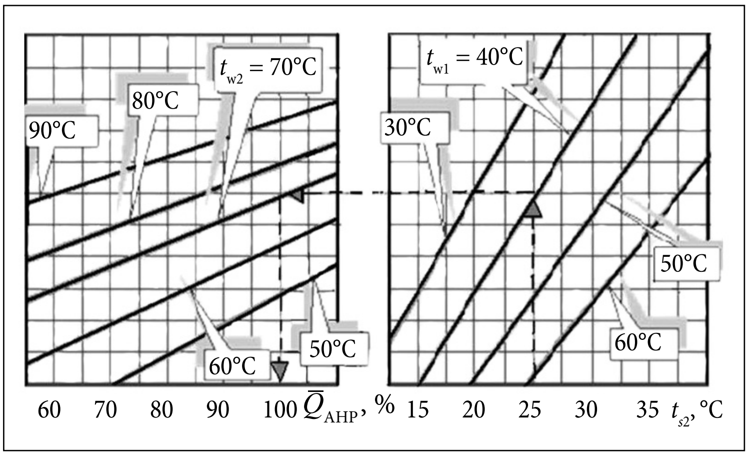

Fig. 2. Change in AHP relative thermal performance $\bar{Q}_{AHP}$ (a) and the temperature of the cooled water after the pump t_{s2} (b) depending on the temperature of the heated water: t_{w1} – at the inlet, t_{w2} – at the outlet of the pump [13]

Table 2. **Characteristics of powerful AHP with steam heating according to a single-stage regeneration scheme of the Broad Corporation brand BDS [3]. COP = 1.71, $\Delta t_w = t_{w2} - t_{w1} = 30°C$**

Heat capacity $Q_{\text{n AHP}}/Q_s$, kW	CW:		RNW:		Flow rates:	
	G_s, m³/h	ΔP_s, kPa	G_w, *m³/h*	ΔP_w, kPa	G_h, kg/h	N_{AHP}, kW
16947/6980	15188	58	1200	83	486	38.8
22595/9304	20240	58	1600	83	648	50.4

– pressure losses for HPU heat carriers: cooled ΔP_s and heated ΔP_w;

– electric power $N_{\text{e AHP}}$ HPU;

– standard costs of AHP heat carriers: $G_{\text{h n}}$, $G_{\text{s n}}$, $G_{\text{w n}}$ for heating, cooling and heating, depending on HPU nominal power $Q_{\text{n AHP}}$ in kW, respectively.

Based on (1, 2), the listed approximation dependencies, an algorithm, and a program in Fortran G95 to determine the characteristics of AHP were built.

MATHEMATICAL MODEL OF TURBINE THERMAL SCHEME

The PT-60 TS was modelled using the energy method [14]. The desire to bring the calculation results closer to the actual ones led to the use of the factory approximation $N_{\text{LPP}} = F_N(G_{\text{LPP}})$ to determine the power of LPP (see formula in Fig. 3), where G_{LPP} is the steam flow rate at the entrance to the LPP and corrections to N_{LPP} from P_h [12].

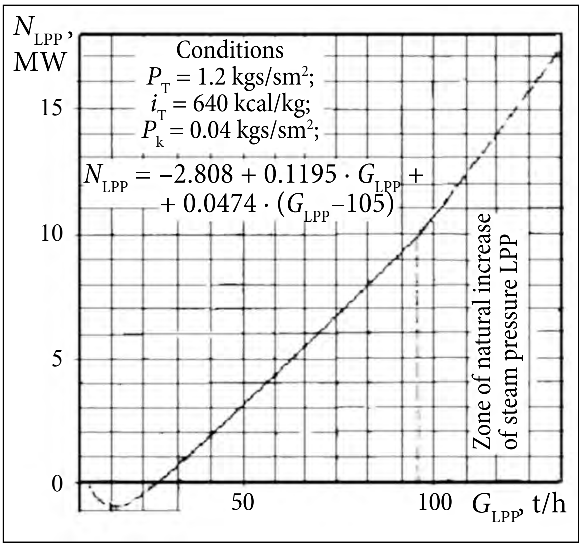

Fig. 3. Internal capacity of PT-60 LPP depending on the steam flow rate according to factory data [12]

When integrating AHP into TS TU, in most cases, it is necessary to increase the steam pressure in the condenser P_k compared to the standard 0.004 MPa, for which the dependence is determined in Fig. 3. This led to the need to make a correction to N_{LPP} from P_k (determined from the similarity of triangles reflecting the process of steam expansion in LPP in the IS diagram), which allows you to set a multiplier to N_{LPP}.

Particular qualities of PT-60 simulation are realised in a software package based on the calculation of the steam turbine TS, developed at Anatolii Pidhornyi Institute of Mechanical Engineering Problems NAS of Ukraine.

$$\tau_{\text{pbp AHP}} = I_{\Sigma\ \text{AHP}} / Pr_{\Sigma\ \text{AHP}}, \tag{3}$$

where $I_{\Sigma\ \text{AHP}} = c_{\text{AHP}} \cdot Q_{\text{n AHP}} + c_{\text{USSM}} \cdot N_{\text{USSM}}$ – total investments, here c_{AHP} – the unit cost of AHP, N_{USSM} – utilisation steam screw machine (USSM) nominal power with the unit cost c_{USSM}. This machine for the integrated PT-60 is necessary for the utilization of steam pressure from the heating HPU production selection. The cost of USSM is 30–40% lower than the cost of a small steam turbine with a backpressure of the same power [14].

The total annual profit from HPU realisation consists of profit from the heating and partial heat load periods

$$Pr_{\Sigma\ \text{AHP}} = Pr_{\text{heat AHP}} + Pr_{\text{int.heat AHP}} =$$

$$Pr_{\text{heat AHP}} + (1 + \overline{Pr}_{\text{AHP}}), \tag{4}$$

where $-Pr_{\text{AHP}} = Pr_{\text{int.heat AHP}} / P_{\text{heat AHP}}$ – relative contribution of profit from the partial heat load period.

The profit during the integration of AHP into the TS of the steam turbine during time τ was calculated

$$Pr_{\text{int.heat AHP}} = \Delta Pr_{\text{heat}}(t_{\text{oa}}) \cdot \tau - Ex/12 \cdot 6, \tag{5}$$

where $Pr_{heat}(t_{oa})$ – total changes per hour in the cost of material flows that occur when working with HPU compared to the variant without a pump;

$Ex = 0.075 \cdot I_{AHP} + 56.5$ – change in annual semi-fixed costs associated with the integration of AHP (salaries of additional personnel, costs of spare parts and materials, etc.), which were determined using known normative data [15].

The first component from (5) was determined

$$\Delta Pr_{heat}(t_{oa}) = \Delta N_{eu} \cdot c_e + \Delta B \cdot c_{sf} +$$

$$+ \Delta G_{sfw} \cdot c_{sfw} + \Delta G_{tech\ w} \cdot c_{tech\ w} + \Delta tax, \qquad (6)$$

and consisted of changes per hour in the cost of such material flows of TU: ΔN_{eu} – 'useful' electrical power and costs: ΔB – standard fuel, ΔG_{sfw} – softened feeding water, $\Delta G_{tech\ w} = G_{k\ min} - G_{ct}$ – feeding with technical water (the consumption of CW is reduced by cooling tower G_{ct} and, as a consequence, the volume of its evaporation).

In formula (6) c_e, c_{sf}, c_{sfw}, $c_{tech\ w}$ are, respectively, the prices of the units of measurement of the listed energy components, Δtax – the difference in the payment of the environmental tax for harmful emissions into the atmosphere after the integration of AHP. The latter is determined

$$\Delta tax = \Delta B_{ng} \cdot (m_{CO_2} \cdot h_{CO_2} + m_{NO_x} \cdot h_{m_{NO_x}}),$$

where ΔB_{ng} – the difference in the consumption of natural gas in the boiler unit before and after AHP integration, m_{CO_2}, m_{NO_x} – masses of harmful emissions CO_2 and NO_x into the atmosphere, formed during the burning of 1 t of natural gas, $h_{CO_2} = 0.8047$ USD/t, $h_{NO_x} = 69.045$ USD/t – environmental tax rates in 2023 for these harmful emissions to the atmosphere in Ukraine from a stationary source.

The main contribution to the change in annual costs when integrating AHP into the steam turbine system gives fuel saving, the high price of which increases the chances of obtaining satisfactory results, therefore natural gas was chosen as the fuel in the study (calorific value ~35,000 kJ/m^3 with a density of ~0.7 kg/m^3 [15]).

The figures of harmful emissions of CO_2 and NO_x into the atmosphere when burning 1 t of natural gas (corresponding to ~1.704 t c.f.), is given in [16, 17]; the following amount of harmful emissions is formed: $m_{CO_2} = 2.726$ t/t, $m_{NO_x} = 0.01$ t/t.

In the conditions of central Ukraine, the partial heat load period lasts ~ 4404 hours (~ six months). In this case, a powerful 'T' or 'PT' turbine at a thermal power plant is in one of the following situations:

– operates in the condensation mode for hot water supply (HWS) or without HWS;

– does not work (there is no need to turn it on if there are several turbines at CHPP, since theoretically the thermal load of hot water supply is 5–6 times less than during heating).

Let us analyse the situation with the working PT-60.

In the condensation mode without HWS (typical, for example, for the Kramatorsk CHPP, which operated on coal), profit from the integration of AHP into the PT-60 heating system with $N_{AHP} > 15$ MW should not be expected since potential heat consumers cannot pay for it.

As can be seen from Fig. 2, operation of PT-60 with AHP on HWS in the condensation mode (with an open RCD with $G_k > 24$ t/h) at a temperature $T_{RNW} = 55°C$ (t_{W1}) is rational after increasing t_{s2} (that is, P_k) and then in the case when the heat losses from the increase in P_k will be less than the achievements of AHP when utilising heat Q_s with a flow rate G_s from the share of CW (to ensure COP > 1.5–1.6).

The characteristics of PT-60 during the partial heat load period with integrated AHP $N_{AHP} = 17.25$ MW (optimal power for the heating period) will study in the next step.

RESULTS

To achieve the goals set, the characteristics of the PT-60 vehicle without HPU were previously calculated when operating during the inter-heating period with different production loads of $G_{i\ p}$ when providing HWS with different flow rates $G_{RNW\ (HWS)}$ and fixed 'useful' generation N_e, which are necessary to determine the change in indicators after the integration of AHP (Table 3).

Next, the PT-60 TS with an integrated AHP (17.25 MW) was calculated when operating during the partial heat load period and the volumes of resources consumed were determined. The scheme of integration of AHP into PT-60 TS is shown in Fig. 4 [12]. Results of calculating the PT-60 TS characteristics with an integrated AHP of 17.25 MW are shown in Table 4.

Table 3. **The state of PT-60 TS in the partial heat load mode without a HPU while ensuring the release of steam from the production extraction with a pressure of 1.296 MPa with different flow rates of RNW for HWS**

Characteristics		Variants:					
		1	2 a	2 b	3 a	3 b	3 c
Steam flow rate per turbine, t/h		144.14	146.85	147.47	155.45	156.44	177.28
Steam consumption in turbine extractions:	– in industrial production, t/h, where:	28.68	38.78	38.81	59.25	59.30	60.42
	– third-party consumer, t/h	**20**	**30**		**50**		
	– HPH 3 for regeneration, t/h	6.95	7.07	7.10	7.45	7.50	8.41
	– LPH 4 for regeneration, t/h	6.18	6.29	6.31	6.63	6.67	7.49
	– LPH 3 for regeneration, t/h	13.53	13.33	13.34	13.03	13.10	15.10
	– in the heating, t/h, where:	42.81	29.54	38.23	35.56	40.42	36.04
	LPH 2 – for regeneration, t/h	4.69	0.85	4.36	5.02	4.69	5.49
	– boiler – t/h	34.80	24.86	29.83	24.85	29.83	24.85
Steam consumption in condenser (pressure 0.004 MPa), t/h		42.72	44.89	40.04	25.115	24.953	43.042
Network water:	– 55°C return (RNW), t/h	**1400**	**1000**	**1200**	**1000**	**1200**	**1000**
	– 70°C straight (SNW), t/h	1428	1020	1224	1020	1224	1020
Consumption:	– CW for cooling tower, t/h	2136	2244	2002	1455	1248	2152
	– water for feeding TU, t/h	12.260	14.465	14.699	19.839	20.088	20.713
Electric capacity:	– own needs, MW	0.785	0.805	0.791	0.790	0.780	0.994
	– 'useful', MW	**30**				**35**	
Electric efficiency, %		0.29878	0.29382	0.29245	0.27817	0.27642	0.28691
Heat supplied to RNW, Gcal/h		19.10	13.65	16.37	13.65	16.37	13.65
Consumption of equivalent fuel per boiler, t c.f./h		14.060	14.307	14.368	15.104	15.194	17.091

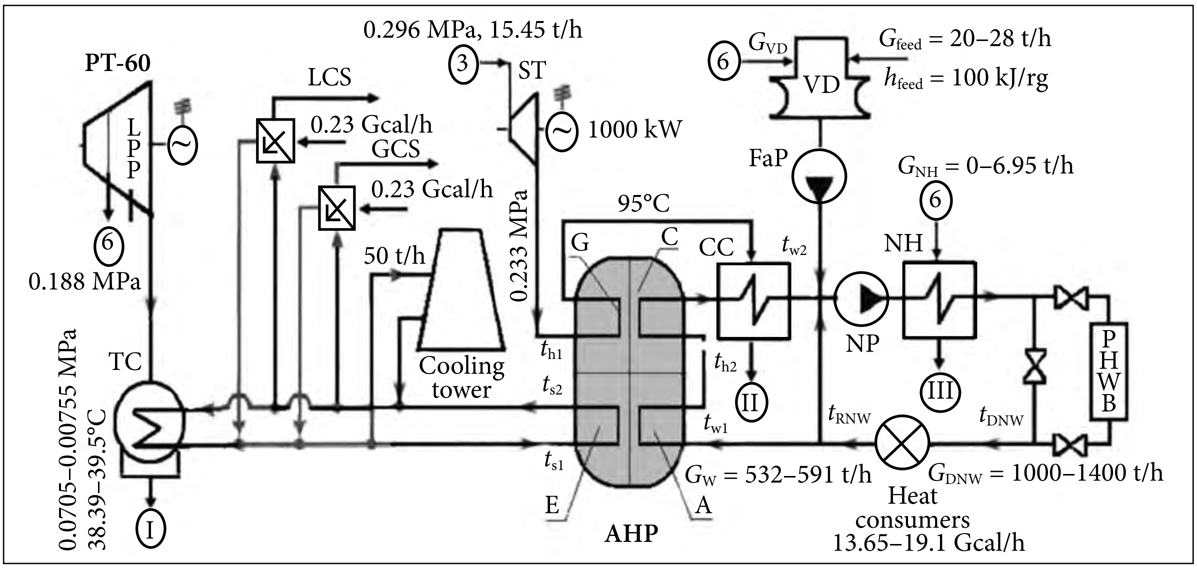

Fig. 4. Principal thermal scheme of the condenser, LCS and GCS cooling system of the PT-60 turbine with the integration of AHP (17.25 MW): AHP: A – absorber, G – generator, E – evaporator, C – condenser, CC – condensate cooler; VD – vacuum deaerator; TK – PT-60 turbine condenser; ST – energy-saving low-power steam turbine with back pressure; pumps: FaP – for heating network feeding, NP – network; PHWB – peak hot water boiler; cooling systems: GCS – generator, LCS – lubricant; NH – network heater; LPP – low pressure part; regulated extractions: 3 – industrial, 6 – heating; I, II, III – connections with elements of the thermal scheme PT-60

Table 4. The state of PT-60 TS during the partial heat load period with an integrated AHP (17.25 MW) at different flow rates: steam from the industrial production extraction with a pressure of 1.296 MPa and network water at the HWS $G_{RNW\,(HWS)}$ at the specified 'useful' electricity generation N_e (USSM power 967 kW, P_{h1} = 0.233 MPa)

Characteristics				Variants:					
				1	2 a	2 b	3 a	3 b	3 c
Steam flow rate per turbine, t/h				143.68	146.45	146.84	154.06	154.37	177.02
Steam consumption in turbine extractions:	– in industrial production, t/h, where:			44.06	54.22	54.24	74.63	74.65	75.87
	– third-party consumer, t/h			**20**	**30**		**50**		
	– HPH 3 for regeneration, t/h			6.93	7.05	7.07	7.39	7.40	8.40
	– at AHP, t/h			15.46					
	– LPH 4 for regeneration, t/h			6.16	6.27	6.29	6.57	6.59	7.48
	– LPH 3 for regeneration, t/h			13.68	13.45	13.47	13.08	13.10	15.26
	– in the heating, t/h, where:			14.91	8.71	10.69	10.01	12.01	11.03
	– LPH 2	– for regeneration, t/h		4.63	4.88	4.67	4.32	4.14	5.34
	– boiler	– t/h		6.95	0	1.98	0	1.98	0
		(heat, Gcal/h)		(3.82)	(0)	(1.086)	(0)	(1.086)	(0)
	– VD	– t/h		1.463	1.045	1.254	1.045	1.254	1.045
		(heat, Gcal/h)		(0.822)	(0.585)	(0.703)	(0.585)	(703)	(0.585)
Absorption heat pump	Heating steam	Flow rate	Inlet	P_{h1} = 0.233 MPa, t_{h1} = 129°C					
		G_h = 15.46 t/h	Outlet	P_{h2} = 0.099 MPa, $t_{h1} = t_{w2}$					
		Heat for regeneration, Gcal/h		1.242					
	Cooled water	Inlet: P_{s1} = 0.02 MPa, t_{s1}, °C		39.5	38.39	39.5	38.39	39.5	38.39
		Outlet: P_{s2} = 0.15 MPa, t_{s2}, °C		34.5	33.39	34.5	33.39	34.5	33.39
		Flow rate G_s, (decrease in CW feeding), t/h		1265 (25.3)	960 (19.2)	1265 (25.3)	960 (19.2)	1265 (25.3)	960 (19.2)
		Heat is removed Q_s, MW		7.24	5.392	7.24	5.50	7.24	5.50
	Heated water	Inlet:		P_{w1} = 0.25 MPa, $t_{w1} = t_{RNW}$					
		Outlet: P_{w1} = 0.0385 MPa, t_{w2}, °C		80.3	80.3	80.3	80.3	80.3	80.3
		Flow rate G_w, t/h		591.2	532.4	591.2	532.4	591.2	532.4
	Heat supplied to RNW, Gcal/h			15.03	13.54	15.03	13.54	15.03	13.54
	Pumps electric power, kW			40.2	36.2	40.2	36.3	40.2	36.3
	Relative heat capacity			0.998	0.899	0.998	0.899	0.998	0.899
	COP			1.537	1.537	1.707	1.537	1.707	1.537
Condenser:	– pressure $P_k \cdot 10^3$, MPa			7.55	7.05	7.55	7.10	7.55	7.10
	– flow rate, t/h			54.65	53.27	51.502	38.10	36.311	52.24
Network water:	– 55°C return (RNW), t/h			**1400**	**1000**	**1200**	**1000**	**1200**	**1000**
	– 70°C straight (SNW), t/h			1428	1020	1224	1020	1224	1020
Flow rate:	– CW for cooling tower, t/h			1467	1653	1310	945	550	1652
	– water for feeding TU, t/h			12.241	14.450	14.674	19.784	20.005	20.702
Electric capacity:	– own needs, MW			0.786	0.793	0.791	0.781	0.773	0.932
	– 'useful', MW			**30**					**35**
Electric efficiency, %				0.29035	0.28518	0.28447	0.27170	0.27107	0.27948
Heat supplied to RNW, Gcal/h				19.1	13.65	16.37	13.65	16.37	13.65
Consumption of equivalent fuel per boiler, t c.f./h				14.015	14.274	14.306	14.975	15.005	17.072

The following parameters were considered in the calculations:

– nominal steam parameters at the turbine inlet;

– boiler installation efficiency is the same as the PHWB (90%);

– relative effective efficiency of the flow part: HPC (80%), MPP (82%), LPP (65.5%);

– in industrial production extraction, consumption of a pair of $G_{\mathrm{i\,p}}$, $[G_{\mathrm{i\,p}}]_{\max}$ = 150 t/h (sent: to production, to HPH 3, to feed water deaerator) with parameters: 1.296 MPa, 280°C. 75% of condensate is returned at a temperature of 40°C;

– throughput of regulated heating extraction of steam $[G_{\mathrm{heat}}]_{\max}$ = 150 t/h (for boiler, LPH 2, for atmospheric and vacuum deaerators (VD)). The steam parameters in the extraction during the partial heat load period are unchanged P_{heat} = 0.03469 MPa, t_{heat} = 71°C (RCD is open);

– supply of network water is 2% with a temperature of 20°C;

– since the steam flow to the condenser G_{k} < 70 t/h, $[G_{\mathrm{k}}]_{\max}$ = 160 t/h, LPH 1 is disabled (G_7 = 0) as is recirculation to the condensate collector.

Load $G_{\mathrm{i\,p}}$ was chosen to be quite small, which in many cases is typical for modern Ukraine (a large load, as expected, gives better economic results). Modes with N_{e} > 30 MW (except for the option N_{e} = 35 MW) were not studied, since according to the results of [11], the higher N_{e} at a given thermal load, the lower the efficiency of the scheme with AHP.

In Table 3 shows that with a fixed $G_{\mathrm{i\,p}}$, a change in $G_{\mathrm{RNW\ (HWS)}}$ has a noticeable effect only on the changes in steam consumption in the heating extraction.

When calculating each mode of PT-60 TS (without HPU or with AHP), the steam flow rate at the turbine inlet G_{t} was selected, providing the specified steam flow and parameters for production extraction, the required temperature of SNW, and the specified N_{e}.

Steam for heating HPU was taken from a controlled industrial production extraction with a pressure of ~1.296 MPa (see diagram in Fig. 4). At the input of the HPU, there is steam with pressure P_{h1}, which comes from the exhaust of the USSM with a power of ~1 MW, installed for energy saving.

The revealed one-sided influence of P_{h1} on the consumption of conventional fuel, it was determined that the rational value of $P_{\mathrm{h1}} \approx 0.233$ MPa lies at the lower confines of the changes range.

In PT-60, it is possible to use 1000 t/h or more for hot water supply during the partial heat load period (during the heating period $G_{\mathrm{RNW\ (HWS)}}$ up to ~1900 t/h) only if there are several steam turbines at CHPP (there are at least three such CHPPs in Ukraine).

The variant without HPU (Table 3) is calculated at a steam pressure in the condenser P_{k} = 0.004 MPa, variants with AHP – at P_{k} = 0.007–0.00755 MPa, which is associated with the desire to provide higher COP (at P_{k} = 0.00755 MPa COP = 1.71).

Since N_{e} was unchanged, the main factor influencing the operating efficiency of PT-60 with AHP is the consumption of conventional fuel $B_{\mathrm{c.f.}}$ in Fig. 5, from which it is clear that during this period, the rational value of the pressure in the TU condenser is P_{k} = 0.00705 MPa.

The choice of rational P_{k} values was implemented for all variants of PT-60 operation during the partial heat load period with an integrated AHP (17.25 MW), which is contained in Table 4, which shows that:

– steam consumption for heating AHP G_{h} = 15.46 t/h and the corresponding Q_{h} = 8.81 Gcal/h were recorded in the calculations;

– in AHP only part of RNW is heated (G_{w} = 525.6–591.2 t/h), therefore there is no question of HPU heating the feeding water;

– at $G_{\mathrm{RNW\ (HWS)}}$ = 1200 t/h for HWS heating, the thermal power of AHP 17.25 MW is not enough (COP = 1.707) – the boiler helps.

Results of calculating changes in indicators the operation of PT-60 without HPU and with AHP 17.25 MW during the partial heat load

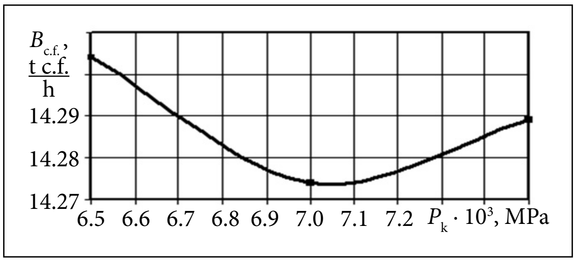

Fig. 5. Dependence $B_{\mathrm{c.f.}}$ from P_{k} for PT-60 with AHP 17.25 MW during the partial heat load period, $G_{\mathrm{i\,p}}$ = 30 t/h, $G_{\mathrm{RNW\ (HWS)}}$ = 1000 t/h, N_{e} = 30 MW

Table 5. **Change in PT-60 indicators after integration $Q_{n\,AHP} \approx 17.25$ MW (see Tables 3 and 4)**

Characteristics			**Variants:**					
			1	**2 a**	**2 b**	**3 a**	**3 b**	**3 c**
Decrease during standing:	– electricity for sale, GWh		0					
	– total conventional fuel consumption, t c.f		166.5	122.1	229.4	477.3	699.3	70.3
	– feeding costs:	– CW to the cooling tower, thousand t	49.506	43.734	51.208	37.74	51.652	37
		– softened water, t	70.3	55.5	92.5	203.5	307.1	40.7
	– emissions CO_2, t		266.4	195.3	367.0	763.6	1118.7	112.5
	– emissions NO_x, t		1.40	1.02	1.93	4.01	5.87	0.59
The changes of cost in indicators from AHP integration:	– total conventional fuel consumption, thousand USD		51.448	37.729	70.885	147.486	216.084	21.723
	– feeding costs:	– CW, thousand U SD	9.901	8.747	10.242	7.548	10.330	9.901
		– softened water, thousand USD	0.703	0.555	0.925	2.035	3.071	0.407
	– payment of environmental tax	– CO_2, thousand USD	0.214	0.157	0.295	0.614	0.900	0.090
		– NO_x, thousand USD	0.096	0.071	0.133	0.277	0.405	0.041
		– total, thousand USD	0.310	0.228	0.428	0.891	1.305	0.131
	Total savings (profit) $Pr_{\text{int.heat AHP}}$ for the partial heat load period, thousand USD		62.364	47.259	82.479	157.960	230.791	29.661

period is presented in Table 5. They were carried out at the following prices: for electricity c_e = 0.13 USD/(kWh), for fuel – natural gas $c_{c.f.}$ = 309 USD/t c.f. (16.5 UAH/m^3 with VAT (value added tax), exchange rate 1 USD – 37.28 UAH), for c_{sfw} = 10 USD/t and $c_{\text{tech w}}$ = 0.2 USD/t [15].

Data from Table 5 indicate that with the AHP integration into PT-60 TS during the partial heat load period, there is a decrease in fuel and feeding water consumption and harmful emissions into the atmosphere. In all studied variants, there is a profit that ranges from ~29,660 USD to ~230,790 USD. The main contribution to this amount comes from fuel economy. There is no increase in electricity generation during HWS from TU with an integrated AHP [11].

RESULTS AND DISCUSSION

Contribution from the integration of AHP 17.25 MW into the PT-60 TS for the partial heat load period $Pr_{\text{int.heat AHP}}$ illustrated together with the results of calculating the annual total financial changes $Pr_{\Sigma\ \text{AHP}}$ and changes during the heating period $Pr_{\text{h.p AHP}}$ (see Fig. 6). Energy prices were the same. RNW consumption during the heating period $G_{\text{h.p RNW}}$, which was set and displayed in this figure, was also selected from the conditions for achieving a level of return on investment, which is close to the promising values.

The relative contribution of profit from the integrated AHP 17.25 MW during the partial heat load period –Pr$_{\text{AHP}}$ is:

– for variant 1 with $G_{\text{i p}}$ = 20 t/h, it is insignificant ~2.4% ($Pr_{\text{h.p AHP}}$ ~1,240,000 USD, $G_{\text{h.p RNW}}$ = 1600 t/h) and ~3.8% ($Pr_{\text{h.p AHP}}$ ~760,000 USD, $G_{\text{h.p RNW}}$ = 1500 t/h);

– for variants 3a and 3b with $G_{\text{i p}}$ = 50 t/h ~11.8% and ~17.3% ($G_{\text{h.p RNW}}$ = 1600 t/h, $Pr_{\text{h.p AHP}}$ = 1,345,000 USD) and ~17% and ~24.9% ($G_{\text{h.p RNW}}$ = 1500 t/h, $Pr_{\text{h.p AHP}}$ = 930,000 USD).

Knowing –Pr_{AHP} (see (4)), it is easy to assess the impact on $\tau_{\text{pbp AHP}}$ of the profit from the integration AHP 17.25 MW during the partial heat load period:

– if $G_{\text{i p}}$ = 20 t/h and $G_{\text{int.heat RNW}}$ = 1400 t/h then $\tau_{\text{pbp AHP}}$ will decrease on 3.6% and 2.3% ($G_{\text{h.p RNW}}$ 1500 t/h and 1600 t/h, respectively);

– if $G_{\text{i p}}$ = 50 t/h, $G_{\text{int.heat RNW}}$ = 1000–1200 t/h, then $\tau_{\text{pbp AHP}}$ will decrease on 14.6–20% ($G_{\text{h.p RNW}}$ = 1500 t/h) and 10.6–14.7% ($G_{\text{h.p RNW}}$ = 1600 t/h), respectively;

– with $G_{\text{i p}}$ = 30 t/h – intermediate results.

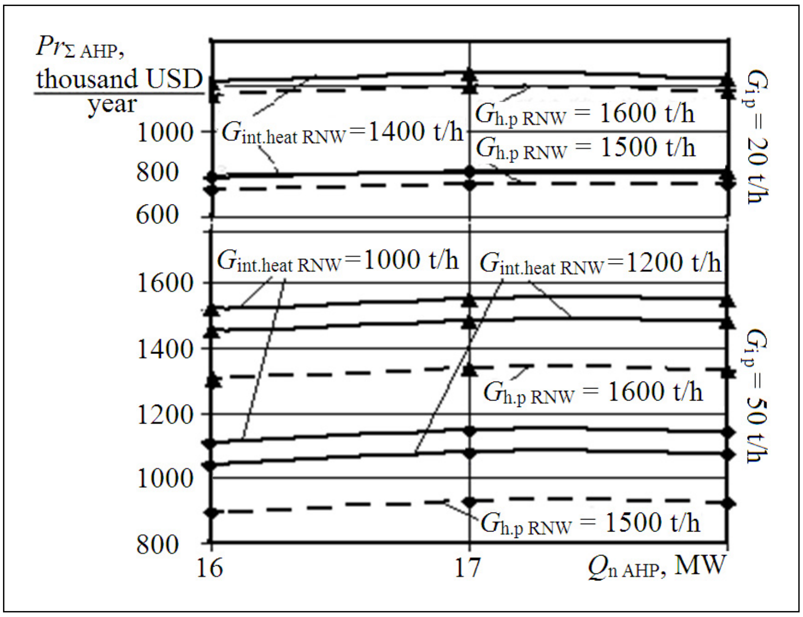

Fig. 6. Dependence of annual profit $Pr_{\Sigma\ \mathrm{AHP}}$ on the nominal thermal power of AHP $Q_{\mathrm{n\ AHP}}$ integrated into the PT-60 TS at various costs of $G_{\mathrm{i\ p}}$ and G_{RNW}

The results obtained showed a positive effect from the realisation of AHP during the partial heat load period. Profit values contribute to reducing the payback period of the project.

CONCLUSIONS

The characteristics of PT-60/70-130/13 steam turbine TS with an integrated AHP of 17.25 MW (optimal thermal power) during the interheating (spring and autumn) period were determined using a mathematical model built by using interpolation dependencies of HPUs work characteristics. They were determined at different flow rates of return network water and steam released from the turbine production extraction with a pressure of 1.296 MPa with a fixed 'useful' electrical power of 30 MW.

When integrated into the thermal scheme of a turbine unit during the partial heat load period (with a $G_{\mathrm{i\ p}}$ = 20–50 t/h), the AHP payback period can be reduced by 2.3–19% (the higher the thermal load, the greater the decrease).

Integration of AHP with a thermal capacity of 17.25 MW into the PT-60 TS when operating during the partial heat load period of 3700 hours (~704 hours of repair) with $G_{\mathrm{i\ p}}$ = 50 t/h, $G_{\mathrm{int.heat\ RNW}}$ = 1200 t/h leads to:

– savings: fuel on ~1.2% (~699 t c.f.), technical water for feeding the circulation system on ~44%, softened water for feeding the turbine unit on ~0.4% (additional costs are taken into account);

– a tangible environmental effect due to the reduction of harmful gas emissions into the atmosphere: CO_2 on ~1118.7 t, NO_x on ~5.87 t, thermal emissions, as well as saving ~41,000 t of water. AHP realisation is additional cost. The environmental effect is achieved by decreasing fuel consumption per energy installation. At this stage, decrease of emissions estimates is preliminary. Carrying out accurate estimates of emissions decreasing is a separate task, which will take into account the exact values of the thermodynamic system efficiency, the quality of the fuel burned, the energy system actual operating conditions, and so on.

Research on the integration of AHP should be continued, since, for example, due to the expected relative reduction in investment, there is hope to obtain a lower calculated $\tau_{\mathrm{pbp\ AHP}}$ of a similar project for the T-110/120-130 turbine.

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Aleksandr Shubenko, Mikola Babak,
Oleksandr Senetskyi, Yana Forkun

ENERGIJOS TAUPYMAS DALINĖS ŠILUMOS APKROVOS LAIKOTARPIU Į GARO TURBINOS PT-60/70-130/13 ŠILUMINĘ SCHEMĄ ĮTRAUKIANT ABSORBCINĮ ŠILUMOS SIURBLĮ SU GARO PAŠILDYMU

Santrauka

Straipsnyje pristatytas iškelto uždavinio nustatyti absorbcinio šilumos siurblio (AŠS) su garo šildymu (COP perskaičiavimo koeficientas = 1,71), integruoto į garo turbinos PT-60/70-130/13 šiluminį kontūrą, kuris išleidžia garą ir karštą vandenį, veikimo efektyvumą tarpiniu šildymo laikotarpiu, rezultatai. Išnagrinėti garo turbinos PT-60/70-130/13 su integruotu absorbcinio šilumos siurbliu, kurios galia ~17,25 MW, veikimo variantai tarpinio šildymo laikotarpiu, kai reguliuojamos turbinos tiekiamo garo parametrai buvo 1,296 MPa ir 280 °C, taikant 20, 30 ir 50 t/h debitą, su kintama karšto vandens tiekimo šilumine apkrova, kurią lėmė grįžtamojo tinklo vandens suvartojimas 1 000–1 400 t/h, o elektrinė galia siekė 30 MW. Esant elektros energijos kainai 0,13 USD/kWh ir kuro kainai 309 USD/t, 17,25 MW absorbcinio šilumos siurblio kaip garo turbinos PT-60/70-130/13 dalies tarpinio pašildymo laikotarpis, kai gamybos apkrova 20–50 t/h. garo, kai grįžtamojo tinklo vandens suvartojimas šilumos tiekimo 1 000–1 200 t/h atsipirkimo laikotarpis sumažėjo iki 2 metų. Tuo pat metu tarp šildymo laikotarpio, kuris Ukrainoje trunka ~4 404 valandas, kuro sutaupoma iki ~1,2 %, techninio vandens cirkuliacinei aušinimo sistemai maitinti – iki 44 %, o minkštinto vandens – 0,4 %. Apčiuopiamas aplinkosauginis efektas pasiekiamas dėl sumažėjusių į atmosferą išmetamų kenksmingų teršalų: faktinės šilumos, pavojingų dujų: CO_2 – 1118,7 t., NO_x – 5,87 t., sutaupoma ~41 tūkst. t techninio vandens.

Raktažodžiai: energijos taupymas, garo turbina, absorbcinis šilumos siurblys, karšto vandens tiekimas, tarpinis šildymo laikotarpis