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OPTIMAL THERMAL OUTPUT OF AN ABSORPTION HEAT PUMP WITH STEAM HEATING INTEGRATED IN A PT-60/70-130/13 STEAM TURBINE

Oleksandr L. Shubenko
shuben@ipmach.kharkov.ua
ORCID: 0000-0001-9014-1357

Viktoriia O. Tarasova
vat523710@gmail.com
ORCID: 0000-0003-3252-7619

Mykola Yu. Babak
Bab67Nik@gmail.com
ORCID: 0000-0002-4281-2790

Oleksii Yu. Boiarshynov
aleksey.boiarshynov@gmail.com
ORCID: 0000-0003-3412-3212

Anatolii Pidhornyi Institute
of Power Machines and Systems
of NAS of Ukraine,
2/10, Komunalnykiv str., Kharkiv,
61046, Ukraine

The problem of determining the optimal thermal power of the absorption bromide-lithium heat pump (AHP) with steam heating, integrated into the thermal scheme of the PT-60/70-130/13 steam turbine when operating in the mode with a slight opening of the rotary regulating diaphragm, was formulated and solved. The turbine plant released steam to consumers and provided heat according to the schedule of 150 / 70 ºC. The characteristics of AHP were modeled using approximate dependencies based on the characteristics of thermotransformer manufacturers. AHP was heated by steam from the production selection of the turbine after the steam screw machine installed for energy saving. The general optimization problem with the objective function of total changing the monthly fuel consumption after the integration of AHP, based on the average monthly outdoor air temperature in the heating season in Ukraine, was divided into 6 auxiliary optimization problems. The control parameters of these problems were: thermal capacity of the AHP, steam pressure in the turbine condenser and at the inlet to the heat pump, steam pressure in the turbine headю These problems were solved by the coordinate descent method. Modes with steam consumption in the production selection of the turbine for the consumers were studied: 15, 30 and 45 t/h (with parameters: 1.296 MPa, 280 ºC) and mains water: 1600, 1650 and 1700 m^3*/h. Their feature is the provision of "useful" generation in volumes corresponding to the work of PT-60/70-130/13 without AHP with a closed rotary diaphragm. For all considered options of the turbine load, the optimal power of the integrated AHP is defined as 20 MW. During the heating period PT-60/70-130/13 with AHP 20 MW when operating in a mode close to the thermal load with the lower of the studied consumptions of production steam and mains water leads to savings of: fuel by ~3.5%, softened water by 8.5%, technical of water by 79.9%, as well as to a noticeable ecological effect due to the reduction of harmful emissions into the atmosphere. The preliminary payback period of AHP is close to 3 years. It is noted that the option of the integrated turbine with a partially open regulating diaphragm at the accepted prices for fuel and electricity loses in terms of economic indicators to the option with a closed diaphragm.*

Keywords*: energy saving, absorption heat pump, steam turbine thermal scheme.*

Introduction

One of the modern energy saving means for utilization of heat Q_{Σ} emitted into the atmosphere by a steam turbo generator is integrated into the thermal scheme of the AHP heat turbine with steam heating, which is confirmed by a sufficient number of papers [1–22] and others.

Projects for integrating such AHPs into a steam turbine have been implemented in a number of countries, most notably in the East [5–7]. In China, the requirement for their installation during the construction of CHPPs is enshrined at the legislative level. These are, as a rule, AHPs with a thermal capacity of 20–30 MW.

Chinese AHPs have been installed, for example, in Riga at a combined heat and power plant [8], at OJSC "SvetlogorskKhimvolokno" in Belarus [9].

In the EU, the installation of AHPs heated by flue gases is of greater interest [4, 10].

It is assumed that the most promising for the AHPs integration are primarily powerful "PT" and "T" turbines operating with a high thermal load [1–3, 20–22]. Under current conditions in Ukraine, steam turbines PT-60/70-130/13 (PT-60) and T-100/110-130 are installed at CHPPs (in particular, currently there are five of the former ones, seven more of PT-60-90/13 ones that are quite close to them, and six of the latter ones). Based on this, we will consider the PT-60 turbine, the most popular among the produced ones, as the object of research into the integration of AHP.

The PT-60 turbine at nominal load with a condenser flow of 12 t/h of steam (the rotary diaphragm is sealed and closed) with a cooling water flow loses thermal power of ~7.37 MW, to which the power of the generator and oil cooling systems $Q_{\text{gcs+ocs}}$~0.47 MW are added [1]. As a result, the cooling tower emits Q_{Σ}~7.84 MW of heat.

In Ukraine, PT-60s of the 1970s are used, their rotary diaphragm is usually not sealed (according to factory data [23], the idle steam consumption G_{c}=24 t/h), and twice as much heat is emitted.

State of the problem. Purpose of the paper

The integration of AHP with steam heating in PT-60 is discussed in papers [1–2], which provide several examples of calculating the operating modes of this turbine, integrated AHP ~17.5 MW, heated by steam from the selection with a pressure of ~0.52 MPa, network water consumption from 1600 t/h to 4200 t/h, steam consumption in the condenser of 12 t/h. When integrating AHP, there is a decrease in electricity generation. In addition, the aforementioned papers highlight the advantages of this energy-saving technology: according to estimates, the return on investment is less than 2.5 years. The papers of the authors of this one [20–22] and the papers of some other scientists are devoted to the outlined issue.

Let's consider in more detail the papers of the authors of the current one, since this study is their continuation.

In paper [20], the problem of determining the optimal nominal thermal power of AHP $Q_{\text{AHP}}^{\text{nom opt}}$ is formulated and solved with steam heating, integrated into the PT-60 TS, operating during the heating period with a significant thermal load. The latter was determined by the consumption of steam to the consumer in the production selection of the turbine $G_{\text{steam}}^{\text{cons}}$ and reclaimed water G_{rw} for heat supply with closed rotary diaphragm of heating selection (G_{c}=26 t/h). The approximate mathematical model of the AHP [21], built on the basis of the database of thermal transformer manufacturers, was used. The integration of the AHP with steam heating was studied at a steam pressure in the production selection of the PT-60 under the consumer conditions of 1.296 MPa, which required the installation of a 1 MW utilization screw steam engine for energy saving.

The general optimization problem with the objective function of fuel consumption of the integrated turbine plant was divided into six auxiliary optimization problems by the number of heating months [20]. Each of them had variable parameters: the nominal power of the AHP $Q_{\text{AHP}}^{\text{nom}}$, steam pressure: that which heats the pump, P_{h1}, in the turbine condenser P_{c}, as well as steam consumption per head of PT-60 G_{t}. It was solved by the coordinate descent method. Optimal power of the AHP $Q_{\text{AHP}}^{\text{nom opt}}$ was determined to be ~17.3 MW (rotary diaphragm not sealed, steam consumption in the condenser G_{c}=26 t/h [20]).

At the same time, for each of the 6 months of the heating season, the thermodynamic characteristics of the PT-60 turbine without and with AHP were calculated (based on the average monthly outdoor air temperatures in Ukraine), and then the change in economic indicators after the integration of the heat pump unit. With the appropriate combination of values $G_{\text{steam}}^{\text{cons}}$ 20–80 t/h and G_{rw} 1200–1600 t/h (less with more and vice versa) integrated into PT-60 AHP 17.3 MW during the heating period might pay off in ~2.5 years [20].

The economic effect of AHP integration was achieved mainly due to fuel savings (up to 6% of natural gas). There was also water savings for feeding. A significant environmental effect was observed due to the reduction of harmful emissions into the atmosphere, as well as water conservation [20].

When integrating AHP, a decrease in electricity generation during the heating period by ~2.3% was noted due to the use of steam for heating the heat pump unit [20] (at outdoor air temperatures $t_{\text{oa}}^{\text{i}} > -3.3$ °C).

In [22], the change in thermodynamic characteristics of PT-60 integrated with AHP 17.3 MW at different heat load values during the inter-heating period was studied. It was shown that the operation of AHP during this period reduces its payback period by 10–11%.

The choice of the optimal thermal power of AHP with steam heating, integrated into a steam turbine of a different capacity (not PT-60), operating under conditions different from those under study, was also considered by other authors [2, 13–14, 16]. For example, in [2], based on the methods of passive experiment planning and numerous studies of thermal scheme, the value of the heat flow utilized by AHP, for which the pump power should be selected based on technical and economic feasibility, was determined.

In papers [20–22], the operation of the PT-60 with AHP in the thermal load mode was studied, i.e. with the rotary diaphragm closed with a fixed steam flow rate into the condenser G_{c}=26 t/h, steam pressure in the heating tap of ~0.146 MPa at a constant temperature. Since the AHP extracts heat from the circulating water, heating the network water, increasing the amount of steam entering the condenser by opening the rotary diaphragm theoretically increases the amount of heat that the heat pump unit can utilize. These considerations, as well as the desire to check the effect of changing the steam pressure in the heating tap according to the outdoor air temperature on the performance of the integrated PT-60, were the reasons for conducting this study.

Paper purpose – determine the optimal thermal power of the steam-heated AHP integrated into the PT-60 turbine operating with a partially open rotary diaphragm (26 t/h$\le G_c<$50 t/h). At the same time, after the integration of heat pump unit, the total value of "useful" electricity generation per month $[N_u^e]$ does not change (unlike [20–22], where the rotary diaphragm is closed: G_c=26 t/h=const, and $N_u^e<[N_u^e]$). The obtained data should be compared with the results of [20] to determine the most effective operating mode of the integrated PT-60.

Mathematical modeling

Mathematical model of AHP

The approximate mathematical model of a steam-heated heat pump unit is shown in sufficient detail in [21], let us recall its features.

The efficiency of a heat pump unit is estimated by the conversion coefficient *COP*

$$COP = Q_{\text{AHP}} / Q_h,$$

where Q_{AHP}, Q_h − the amount of heat transferred to the heat pump unit of the coolant that is heated and the one which heats the pump, respectively. A simple AHP with steam heating with single-stage regeneration has on average *COP*=1.71 [24].

In our case, the AHP operates with three energy streams, in the conditions of a power plant with steam heating this is (see Fig. 1 and 2) [20–22]:

– water steam with flow rate G_h, which heats the heat pump unit, (in the case of PT-60 it is taken from the production selection after expansion in the screw machine) with initial parameters: pressure P_{h1} varies in range 0.14–0.6 MPa, temperature t_{h1} 110–150 ºC respectively;

– water with initial temperature t_{s1}, which changes from +7 to +35 ºC, the heat of which is utilized (circulating water of the condenser, generator and oil cooling systems), has a flow rate of G_s, after heat pump unit it is cooled to ~5 ºC;

– water heated to t_{w2} 20–35 ºC (part or all of the reclaimed water), has a flow rate of G_w, initial temperature is t_{w1}.

To model the performance of the AHP, the following were used: performance curves of heat pump unit Air Conditioning (BROAD), China (Fig. 1), nomograms of SKB "Teplosibmash" (Fig. 2) and a number of general characteristics (for more information, see [21]).

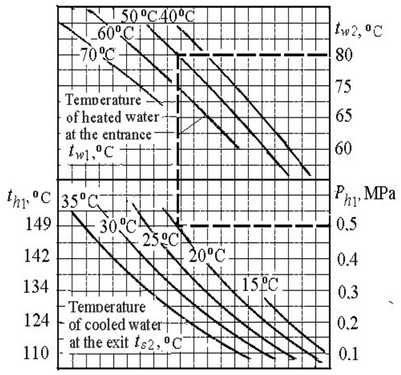


Fig. 1. BROAD AHP performance curves with display of operating parameters [25]:
— — – AHP is heated by steam
with standard parameters: 0.5 MPa, 149 ºC

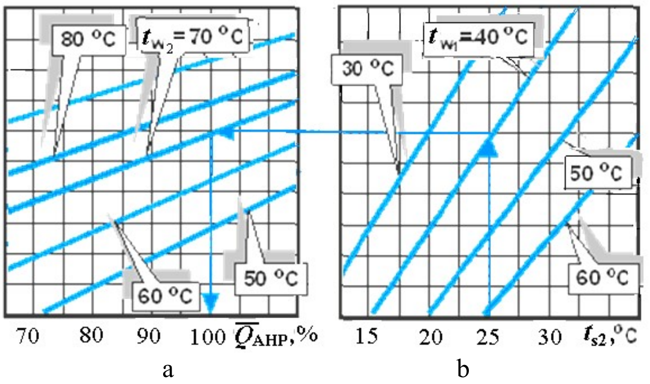


Fig. 2. Change in relative thermal efficiency of AHP (a) and cooled water temperature after heat pump unit $t_{s2}=t_{s1}$–5 ºC (b) depending on the temperature of the water that is being heated:
t_{w1} – at the entrance, t_{w2} – on the exit [26]

For each of the steam pressures P_{h1} (Fig. 1), which heats the AHP, for known temperatures: cooled circulating water at the outlet of the heat pump unit t_{s2} and reclaimed water at the entrance of t_{w1}, the t_{w2} – temperature of the network water heated in the pump – was determined. The table of these values is the basis of the interpolation algorithm that implements the dependence $t_{w2}(P_{h1}, t_{s2}, t_{w1})$.

The table of values of the base points of the lines on the nomograms in Fig. 2 is the basis of the interpolation algorithm that determines the relative thermal power of the AHP $\overline{Q}_{\text{AHP}}(t_{s2}, t_{w1}, t_{w2})$.

Using the BROAD data [25], approximation expressions were also constructed to determine the characteristics of the AHP:

– electrical power consumption $N^{\text{e}}_{\text{AHP}}$;

– pressure losses for heat carriers: ΔP_s, which is cooling, and ΔP_w, which is heating;

– standard flow rate of heating steam (in kg/s), depending on $Q^{\text{nom}}_{\text{AHP}}$ in kW:

$$G^{\text{norm}}_{h}=0.895\cdot Q^{\text{nom}}_{\text{AHP}}/3600=\text{const.}$$

Modeling of turbine TC based on factory specifications

PT-60 is a steam turbine with a condensing unit and two adjustable steam taps. It is a two-cylinder single-shaft unit that has high- and low-pressure cylinders (with parts of medium and low pressure), seven steam taps, three high-pressure and four low-pressure heaters. As well as the following main characteristics [23]:

– nominal turbine power 60 MW;

– speed 3000 rpm.;

– fresh steam parameters before the stop valve: 12.75 MPa, 565 °C;

– steam pressure of regulated taps: production P_{prod} 0.686–1.666 MPa, heat-insulating P_{heat} 0.0294–0.147 MPa.

Let's recall that in Ukraine, PT-60s were produced in the 60s and 70s of the last century, and the rotary diaphragm is not compacted.

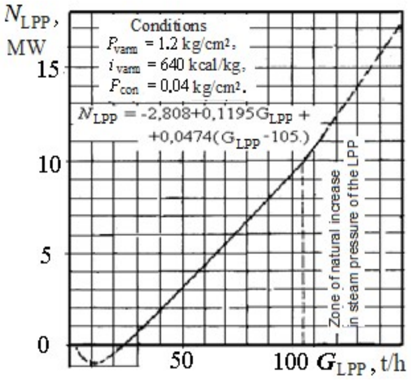


Fig. 3. Dependence of the internal power of the PT-60 low-pressure heaters on the steam consumption according to factory data [23]

The desire to bring the calculation results closer to real data led to the use of factory approximation to determine the power of the low pressure part $N_{\text{lpp}}=F_N(G_{\text{lpp}})$ (see the formula in Fig. 3), where G_{lpp} – steam consumption at the inlet to the low pressure part and corrections to N_{lpp} from P_{heat} [23].

When integrating AHP into the turbine system, the steam pressure in the condenser P_{c} usually exceeds the standard 0.04 kg/cm^2 (see Fig. 3). This led to the need to make amendments to N_{lpp} (multipliers) from P_{c} and P_{heat}, which were determined from the similarity of triangles reflecting the process of pair expansion in the IS diagram, see [20–21].

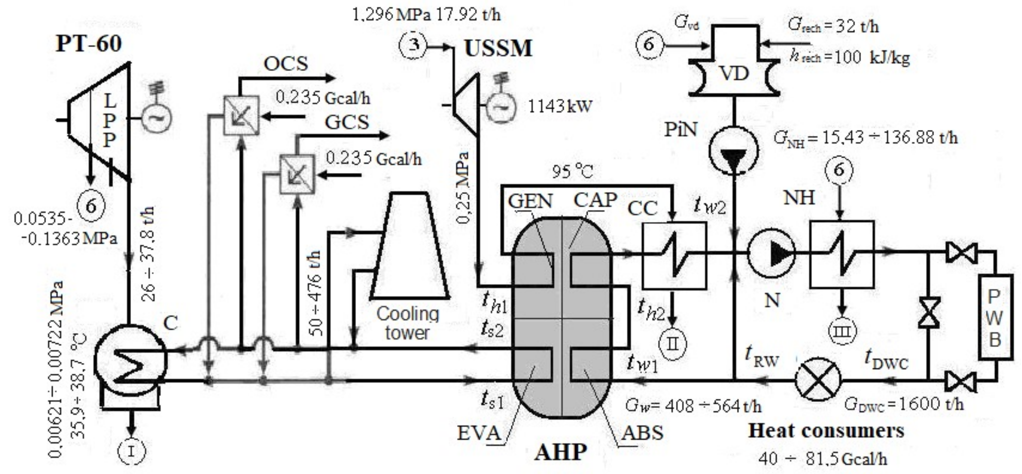
The presented features of modeling by the energy method of a steam turbine thermal scheme integrated with an AHP with steam heating were reflected in the software package developed at the IPMS of the NAS of Ukraine.

Setting the task of choosing the optimal power of the AHP

The scheme of the AHP 20 MW integration in PT-60 is shown in Fig. 4 (see the schematic thermal scheme of this turbine in [23]). As can be seen from this circuit, steam for AHP heating is taken from the regulated production selection of the turbine with a pressure of 1.296 MPa (as at Kramatorsk CHPP). Heat pump unit is heated by steam with a pressure of 0.233 MPa from the exhaust of the utilization steam screw machine with a capacity of 1143 kW, which is installed for energy saving.

The task of finding the optimal nominal power of AHP $Q^{\text{nom opt}}_{\text{AHP}}$ as part of the PT-60 thermal scheme operating during the heating season in a mode close to the heat load, with the specified $G^{\text{cons}}_{\text{steam}}$ and G_{rw} by analogy with [20] is reduced to solution 6 (by the number of heating months in Ukraine n_{heat}) of auxiliary optimization problems.

When solving each of the auxiliary optimization problems, the $Q^{\text{nom}}_{\text{AHP}}$, P_{h1}, P_{c} and G_t vary, and such vectors are considered given:



$\vec{z}_{z\,r}$

Fig. 4. Cooling circuit of the PT-60 turbine condenser system with integrated 20 MW AHP:
AHP: A – absorber, G – generator, E – evaporator, C – condenser, CC – condensate cooler;
VD – vacuum deaerator; KT – PT-60 condenser; USSM – utilization steam screw machine;
pumps: PiN – heating network feed, N – network; PWB – peak water heating boiler;
cooling systems: GCS – generator, OCS – oil; NH – network heater, LPP – low-pressure part;
regulated steam withdrawals: 3 – production, 6 – heating;
I, II, III – connections with elements of the PT-60 thermal circuit

$\vec{t}^{\,\mathrm{i}}_{\mathrm{oa}}$ = {-5.4, -4.5, +0.9, +5, +1, -3, +20} – average monthly outdoor temperatures in ºC;

$\vec{\tau}$ = {744, 672, 744, 732, 720, 744} – duration of idle months $\vec{t}^{\,\mathrm{i}}_{\mathrm{oa}}$ in hours (January, … , half of April + October, … , December), as well as the inter-heating period of 4404 hours;

$\vec{z}_{zr} = \{P_{\mathrm{prod}},\ G^{\mathrm{cons}}_{\mathrm{steam}},\ G_{\mathrm{rw}},\ \ldots\}$ – operating parameters, which include ~40 characteristics in the considered case.

The quality criterion of each auxiliary optimization problem is the change in fuel consumption $\Delta B^{\mathrm{eq}}_{\mathrm{fuel\ AHP}}$, which is burned in a month after the integration of the AHP and is the difference between the fuel consumption of the turbine unit without heat pump unit and the integrated one. It is formulated as follows (basic equations and active constraints are shown):

$$\text{\textit{To find:} } \max(\Delta B^{\mathrm{eq}}_{\mathrm{fuel\ AHP}}(Q^{\mathrm{nom}}_{\mathrm{AHP}},\ P_{h1},\ t_{s2},\ t_{w1},\ t_{w2},\ \vec{z}_{zr})); \tag{1}$$

$$\Delta B^{\mathrm{eq}}_{\mathrm{fuel\ AHP}}(Q^{\mathrm{nom}}_{\mathrm{AHP}},\ P_{h1},\ t_{s2},\ t_{w1},\ t_{w2},\ \vec{z}_{zr}) = -\Delta B^{\mathrm{eq}}_{\mathrm{fuel\ without\ AHP}}(\vec{z}_{zr}) + \Delta B^{\mathrm{eq}}_{\mathrm{fuel\ AHP}}(Q^{\mathrm{nom}}_{\mathrm{AHP}},\ P_{h1},\ t_{s2},\ t_{w1},\ t_{w2},\ \vec{z}_{zr});$$

$$G_{\mathrm{c}} = G^{\mathrm{fact}}_{\mathrm{c}}(t^{\mathrm{i}}_{\mathrm{oa}},\ Q^{\mathrm{nom}}_{\mathrm{AHP}},\ G_{\mathrm{T}},\ P_{h1},\ P_{\mathrm{c}},\ \vec{z}_{zr});$$

$$t_{s2} = t_{s1}(P_{\mathrm{c}}) \text{ -5 ºC};$$

$$t_{w1} = t_{\mathrm{rw}};$$

$$t_{w2} = t_{w2}(P_{h1},\ t_{s2},\ t_{w1});$$

$$Q^{\mathrm{real}}_{\mathrm{AHP}} = \overline{Q}_{\mathrm{AHP}}(P_{h1},\ t_{s2},\ t_{w1},\ t_{w2})\cdot Q^{\mathrm{nom}}_{\mathrm{AHP}};$$

$$G^{\mathrm{norm}}_{h} = 0.895\cdot Q^{\mathrm{nom}}_{\mathrm{AHP}}/3600 = \mathrm{const};$$

$$t_{h2} \approx t_{w2};$$

$$Q_h = G^{\mathrm{norm}}_{h}(i_{h1}(P_{\mathrm{prod}},\ t_{\mathrm{prod}}) - i_{h2}(P_{h2},\ t_{h2}));$$

$$Q_s = Q^{\mathrm{real}}_{\mathrm{AHP}} - Q_h;$$

$$G_s = Q_s / 4.19 / (t_{s1}(P_{\mathrm{c}}) - t_{s2});$$

$$1.36 \le COP(P_{h1},\ t_{s2},\ t_{w1},\ t_{w2}) \le 1.71;$$

$$G_w = Q^{\mathrm{real}}_{\mathrm{AHP}} / 4.19 / (t_{w2} - t_{w1});$$

Mathematical
model of AHP

$$N^{\mathrm{e}}_{\mathrm{ussm}} = G^{\mathrm{norm}}_{h}(i_{\mathrm{prod}} - i_{h1}(P_{h1},\ t_{h1})))\cdot\eta_{\mathrm{ussm}};$$

$$G_{\mathrm{c}}(i_{\mathrm{c}}(P_{\mathrm{c}},\ t_{\mathrm{c}}) - t_{s1}(P_{\mathrm{c}})\cdot 4.19) + Q_{\mathrm{gcs+ocs}} = Q_{\mathrm{s}} + Q_{\mathrm{ct}};$$

$$Q^{\mathrm{real}}_{\mathrm{AHP}} = Q_{150/70}(t^{\mathrm{i}}_{\mathrm{oa}},\ G_{\mathrm{dw}}) - G_{\mathrm{heat}}\cdot i_{\mathrm{heat}}(P_{\mathrm{heat}},\ t_{\mathrm{heat}});$$

$$G_{\mathrm{dw}} = G_{\mathrm{rw}}(1 + \overline{G}^{\mathrm{r}}_{\mathrm{dw}});$$

$$[N^{\mathrm{e}}_{\mathrm{u}}]) = N^{\mathrm{e}}_{\mathrm{u}}\ (t^{\mathrm{i}}_{\mathrm{oa}}, Q^{\mathrm{nom}}_{\mathrm{AHP}}, G_{\mathrm{t}}, P_{h1}, P_{\mathrm{c}}, \vec{z}_{zr}) + N^{\mathrm{e}}_{\mathrm{ussm}} - N^{\mathrm{e}}_{\mathrm{AHP}} \leq 70\ \mathrm{MW};$$

$$k_{\mathrm{cc}} \cdot G_{\mathrm{c}} = G_{\mathrm{ct}} + G_{s};$$

$$26\ \mathrm{t/h} \leq G_{\mathrm{c}} < 50\ \mathrm{t/h};$$

$$15\ \mathrm{t/h} \leq G_{\mathrm{heat}} < 150\ \mathrm{t/h}\ [23];$$

$$15\ \mathrm{MW} \leq Q^{\mathrm{nom}}_{\mathrm{AHP}} \leq 40\ \mathrm{MW};$$

$$140\ \mathrm{t/h} < G_{\mathrm{t}} \leq 387\ \mathrm{t/h}\ [23];$$

$$0.233\ \mathrm{MPa} \leq P_{h1} < 0.6\ \mathrm{MPa};$$

$$50\ \mathrm{t/h} = [G_{\mathrm{ct}}] \leq G_{\mathrm{ct}};$$

$$20\ ^{\circ}\mathrm{C} \leq t_{s1}(P_{\mathrm{c}}) \leq 40\ ^{\circ}\mathrm{C};$$

$$30\ ^{\circ}\mathrm{C} \leq t_{w1}(t^{\mathrm{i}}_{\mathrm{oa}}) \leq 60\ ^{\circ}\mathrm{C};$$

$$50\ ^{\circ}\mathrm{C} < t_{w2}(P_{h1}, t_{s2}, t_{w1}) < 90\ ^{\circ}\mathrm{C}.$$

In statement (1) we have the following thermal capacities:

– $Q^{\mathrm{real}}_{\mathrm{AHP}}(Q^{\mathrm{nom}}_{\mathrm{AHP}}, P_{h1}, t_{s2}, t_{w1}, t_{w2})$ – real, transmitted to the AHP network water;

– $Q_{\mathrm{gcs+ocs}}$ – total cooling flow of generator and oil cooling systems;

– Q_{s} – of the flow of the central heating medium cooled in the AHP;

– $Q_{150/70}(t^{\mathrm{i}}_{\mathrm{oa}}, G_{\mathrm{dw}})$ – supplied to the consumer from the CHPP according to the temperature schedule 150 / 70 ºC;

– $Q_{\mathrm{ct}} \approx 4.19 \cdot k_{\mathrm{cc}} \cdot G_{\mathrm{ct}}$ – of the flow removed from the thermal scheme in the cooling tower, here G_{ct} – steam flow rate in the cooling tower in kg/s, $k_{\mathrm{cc}}=50$ – cooling coefficient.

We also have the components of the vector $\vec{z}_{zr}$: G_{dw} – direct network water consumption, relative consumption of its recharge $\overline{G}^{\mathrm{r}}_{\mathrm{dw}}$, $\eta_{\mathrm{ussM}}=0.8$ – efficiency of the utilization steam screw machine.

During the calculation of thermal scheme, the following were also determined: $N^{\mathrm{e}}_{\mathrm{u}}$ – "useful" electric power generated by the integrated PT-60 (must correspond to $[N^{\mathrm{e}}_{\mathrm{u}}]$ – "useful" generation of the turbine without heat pump unit); $i_{h1}(P_{h1}, t_{h1})$, $i_{h2}(P_{h2}, t_{h2})$, $i_{c}(P_{c}, t_{c})$ – specific heat content of the steam heating the AHP, at the inlet and outlet, respectively, and in the condenser. In addition, the pressure, temperature, flow rate and specific heat content of the steam in the PT-60 taps: P_{prod}, t_{prod}, G_{prod}, $i_{\mathrm{prod}}(P_{\mathrm{prod}}, t_{\mathrm{prod}})$ – in production, P_{heat}, t_{heat}, G_{heat}, $i_{\mathrm{heat}}(P_{\mathrm{heat}}, t_{\mathrm{heat}})$ – in heating (rotary diaphragm – partially open).

Results of determining the optimal power of the AHP

When calculating $Q^{\mathrm{nom\ opt}}_{\mathrm{AHP}}$, it was also set (components of the vector $\vec{z}_{zr}$):

– at the input to the PT-60, the nominal steam parameters are set;

– steam consumption in production selection G_{prod}, $[G_{\mathrm{prod}}]^{\mathrm{max}}=150$ t/h (for production, for three high-pressure heaters, for feed water deaerator, utilization steam screw machine) with parameters: 1.296 MPa, 280 ºC. Condensate return is 75% with temperature 40 ºC;

– mains water recharge 2% G_{rw} with temperature 20 ºC;

– steam flow into the condenser $G_{\mathrm{c}}<50$ t/h, $[G_{\mathrm{c}}]^{\mathrm{max}}=160$ t/h, one low-pressure heaters – switched off ($G_{7}=0$), as well as recirculation to the condensate collector.

The flow rate and parameters of steam in the heat extraction (to the boiler, to the two low-pressure heaters, to the vacuum and atmospheric deaerators) are calculated; the maximum throughput capacity of the extraction $[G_{\mathrm{heat}}]^{\mathrm{max}}=150$ t/h. It limits the generation when the turbine operates at low air temperatures.

The optimization parameters of problem (1) were: $Q^{\mathrm{nom}}_{\mathrm{AHP}}$, P_{h1}, P_{c}, G_{t}. It was solved by the method of coordinate descent. A one-sided influence of P_{h1} at $\Delta B^{\mathrm{eq}}_{\mathrm{fuel\ AHP}}$ was revealed. As a result, $P^{\mathrm{opt}}_{h1} = P^{\mathrm{min}}_{h1} = 0.233$ MPa lies at the lower limit of the range of change.

When solving each of the six auxiliary optimization problems (1), the characteristics of the PT-60 thermal scheme without AHP were previously calculated when operating in the heating period with a constant vector (with specified steam consumption of G_s^c and tap water G_{rw} at P_c=0.0034 MPa). The "useful" electrical power generated without heat pump unit was determined $[N_u^e]$ (should be maintained when calculating the integrated PT-60).

If the pressure of the production steam selection, which heats the AHP, exceeds 0.7–0.8 MPa, it is rational to use a utilization steam screw machine or a small steam turbine with backpressure to utilize the excess pressure. How the power of the latter depends on the AHP power is shown in Fig. 5. The minimum value of Q_{AHP}^{nom}=17.3 MW in this figure and further during the research was chosen based on the results [20].

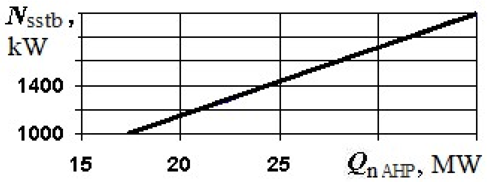
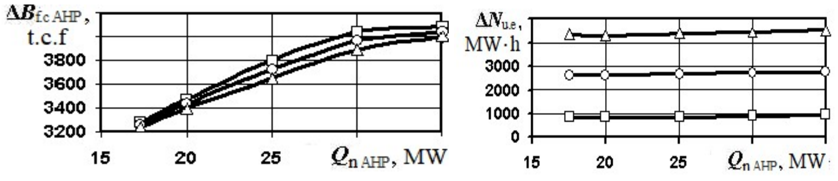


Fig. 5. Dependence of small steam turbine with backpressure power on AHP power

In the course of solving auxiliary optimization problem (1) with t_{oa}^i = -5.4 ºС (January is the coldest month) it turned out that when integrating AHP into the PT-60 thermal scheme, it is impossible to simultaneously provide: G_c≥26 t/h and $[N_u^e]$=48.25 MW (generation without heat pump unit). To meet these conditions, it was necessary to increase the "useful" generation at the optimum point to N_u^e=49.88 MW. At G_{rw}=1700 t/h the same problem exists with t_{oa}^i = -4.5 ºС and -3 ºС. Maximum value of $\Delta B_{fuel\ AHP}^{eq}$ ≈24.05 t.c.f./h is on the border of the permissible area with COP≥1.36 (the limitation was chosen due to greater interest in the range of change Q_{AHP}^{nom}<25 MW) while Q_{AHP}^{nom}=35 MW, P_c=0.00641 MPa, P_{h1}=0.233 MPa.

Having solved six auxiliary optimization problems (1), we found a solution to the general optimization problem. The optimal power of the AHP in the adopted formulation was $Q_{AHP}^{nom\ opt}$=35 MW.

At a given thermal load, the integration of AHP leads to a reduction in the amount of fuel burned $\Delta B_{fuel\ AHP}^{eq}$, changes in generated electricity ΔN_u^e (if $[N_u^e] \neq N_u^e$), reduction of water used, harmful emissions into the atmosphere. Results of calculation of changes during the heating period in two key characteristics of the integrated PT-60 depending on Q_{AHP}^{nom} at different G_{rw} is shown in Fig. 6.



a b

Fig. 6. Change in the integrated PT-60 quantity of fuel burned during the heating period (a) and generated "useful" electricity (b) depending on the power of the AHP at G_{steam}^{cons} =15 t/h and a number of values G_{rw}:
–□– – G_{rw}=1600 t/h; –○– – G_{rw}=1650 t/h; –△– – G_{rw}=1700 t/h

As can be seen from Fig. 6, with increasing power of the AHP integrated into the PT-60:

– $\Delta B_{fuel\ AHP}^{eq}$ increases, although the rate of this process decreases. The condition COP≥1.36 is active and at t_{oa}^i = -5.4 ºС restricts Q_{AHP}^{nom} by the value of 35 MW (see auxiliary optimization problem statement (1));

– ΔN_u^e slowly increases at a given G_{rw}.

As when searching $Q_{AHP}^{nom\ opt}$ it wasn't possible to ensure ΔN_u^e=0, it is possible to simultaneously take into account $\Delta B_{fuel\ AHP}^{eq}$ and ΔN_u^e if we move on to economic assessments.

Economic evaluation of AHP integration

In the conditions of Ukraine at war, it is permissible to choose a simple payback period [20] as the criterion for the economic evaluation of a technical solution, which is determined as

$$\tau_{pb} = I_{\Sigma\ AHP} / Pr_{\Sigma\ AHP},$$

where $I_{\Sigma\,\mathrm{AHP}}=c_{\mathrm{AHP}}\cdot Q^{\mathrm{nom}}_{\mathrm{AHP}} + c_{\mathrm{ussm}}\cdot N_{\mathrm{ussm}}$ – total investments in the implementation of energy technology, here N_{ussm} – nominal power of the utilization steam screw machine, and c_{AHP} and c_{ussm} – specific costs of AHP and screw machine.

Profit for the heating period when integrating AHP into the steam turbine system thermal scheme when averaging over $t^{\mathrm{i}}_{\mathrm{oa}}$ is determined

$$Pr_{\mathrm{hp}} = \sum_{i=1}^{n_{hp}} (\Delta Pr_{\mathrm{hp}\,i}(t^{\mathrm{i}}_{\mathrm{oa}\,i})\cdot \tau_{\mathrm{pb}\,i} - Ex/n_{\mathrm{hp}}), \tag{2}$$

where $\Delta Pr_{\mathrm{hp}\,i}(t^{\mathrm{i}}_{\mathrm{oa}\,i})$ – total change in the cost of material flows per hour of operation of the integrated PT-60 in the heating period compared to the option without heat pump unit, which is calculated when solving the auxiliary optimization problem (1); $Ex = Ex_{\mathrm{AHP}} + Ex_{\mathrm{ussm}}$ – change in annual fixed costs (expenses) associated with the integration of AHP and utilization steam screw machine, respectively (salary of additional personnel, costs of spare parts and materials, repairs, etc.), taking into account the low capacity of utilization steam screw machine [20], we have in thousand of USD: $Ex_{\mathrm{ussM}}=0.075\cdot I_{\mathrm{ussM}}+28.5$, $Ex_{\mathrm{AHP}}=Ex_{\mathrm{ussM}}$.

The main contribution to the change in costs when integrating AHP into the steam turbine system is fuel savings [20], the high price of which increases the chances of obtaining promising results. Therefore, natural gas was chosen as the fuel (calorific value $Q^{\mathrm{w}}_{\mathrm{l}\ \mathrm{ng}}$ ~35000 kJ/m^3 at density ρ_{ng}~0.7 kg/m^3).

For a detailed explanation of the term under the sum sign in expression (2), see [20–22]. The calculations were performed at the prices: for electricity c_{e}=0.13 USD/(kW·h), for fuel $c^{\mathrm{eq}}_{\mathrm{fuel}}$=300 USD/t.c.f.

According to expert assessments of specialists of the Institute of Power Machines and Systems of the National Academy of Sciences of Ukraine, who are engaged in research on water purification for CHPP [25], the following water prices were adopted: softened (chemically purified) c_{cpw}=10 USD/t, technical c_{H2O}=0.2 USD/t.

Investments in AHP integration

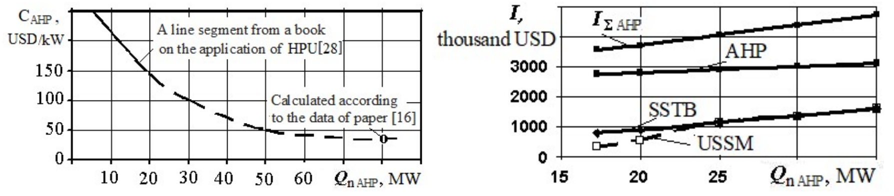
For a preliminary estimate of the cost of installing AHP I_{AHP} we will use the data from literature sources, see Fig. 7, a. The cost of installing the utilization steam screw machine is 30–40% less than a small steam turbine with backpressure of the same capacity [20, 27]. As a result, we have

$$I_{\mathrm{ussm}} = \begin{cases} 350 \text{ thousand USD, if } 0.6\ \mathrm{MW} < N_{\mathrm{ussm}} \le 1\ \mathrm{MW}; \\ N_{\mathrm{ussm}}\cdot c_{\mathrm{ussm}}, \text{ if } 1\ \mathrm{MW} \le N_{\mathrm{ussm}} \le 1.4\ \mathrm{MW}, \end{cases}$$

where c_{ussm}=350 USD/kW.

Utilization steam screw machine with a capacity of more than 1.4 MW are not currently produced. In case if N_{ussM}>1.4 MW, then small steam turbine with backpressure should be installed, c_{sstb}~800 USD/kW [27].

Change in the cost of installing a waste expansion steam engine I_{WESE} (utilization steam screw machine or steam turbine with backpressure), AHP I_{AHP}, as well as total investments for the project implementation $I_{\Sigma\,\mathrm{AHP}}$ depending on the heat pump unit power is shown in Fig. 7, b.



a b

Fig. 7. Dependence of specific costs for the implementation of the AHP integration project (a) the cost of AHP installing, waste expansion steam engine and total investment for the implementation of the project (b) on the capacity of the heat pump unit

Results and discussion

Taking into account the data in Fig. 7, the change in the total annual profit after the integration of AHP into PT-60 was determined at the given $G^{\mathrm{cons}}_{\mathrm{steam}}$ and G_{rw} depending on the capacity of the heat pump unit. According to the results of [22], the income from the integration of AHP in the inter-heating season was assumed to be 50 thousand USD (half of the possible).

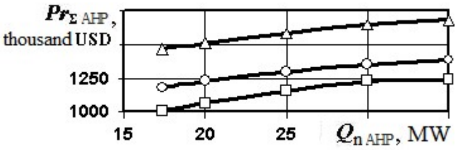
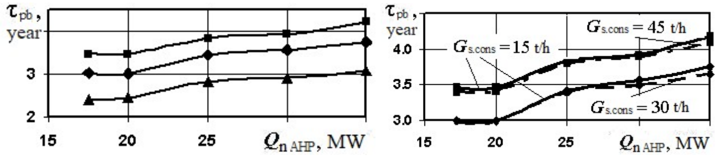


Fig. 8. Change in annual profit from the nominal thermal power of the AHP integrated in the PT-60, with G_{steam}^{cons} =15t/h and a number G_{rw}:

-□- – G_{rw}=1600 t/h;
-○- – G_{rw}=1650 t/h;
-△- – G_{rw}=1700 t/h



a b

Fig. 9. Change in the simple payback period of the AHP integration project in PT-60 by G_{steam}^{cons} =15 t/h (a), G_{steam}^{cons} =30 t/h and 45 t/h (b) depending on the heat output of the pump and at different reclaimed water costs:

-□- – G_{rw}=1600 t/h;
-○- – G_{rw}=1650 t/h;
-△- – G_{rw}=1700 t/h

Integration of AHP in PT-60 under the accepted conditions and G_{rw} brings a fairly significant annual income of 1011–1686 thousand USD (see Fig. 8). The cost of the generated additional "useful" electricity is 113–589 thousand USD (added to the cost of saved fuel when calculating profit). With an increase of Q_{AHP}^{nom} and G_{rw} income is increasing.

The simple payback period of the AHP integration project was calculated τ_{pb}, its change from the heat pump power for three reclaimed water flows at three values G_{steam}^{cons}. The results are shown in Fig. 9.

With growth of G_{rw}, AHP τ_{pb} payback period decreases. The range of changes in the network water flow in Fig. 9 gives an idea of the thermal load of PT-60, at which the integration of AHP is promising.

In the interval of 17.3 MW<Q_{AHP}^{nom}<20 MW payback period of AHP, as can be seen from Fig. 9, a, has minimum values 2.4<τ_{pb}<3.5. Moreover, at a given G_{rw} it practically does not change. Any value can be chosen as optimal Q_{AHP}^{nom} from this interval.

Quite a weak influence of the steam consumption released to the consumer G_s^c, for the payback period of the project of integrating AHP with steam heating in the PT-60 thermal scheme demonstrate the dependencies shown in Fig. 9, b.

Table 1. Change in PT-60 indicators after integration of $Q_{AHP}^{nom\ opt}$ =20 MW at G_{steam}^{cons} =15 t/h, G_{RW}=1600 t/h. Utilization steam screw machine capacity ~1143 MW

Indicator name			Months						In total
			I	II	III	IV, X	XI	XII	
Average monthly air temperature t_{oa}^{i}, °C			-5.4	-4.5	+0.9	+5.0	+1.5	-3.0	
Temperature t_{oa}^{i} idle time, h			744	672	744	732	720	744	
Change per month	electricity for sale, GW·h		852.000	-0.060	0.052	0.040	0.068	-0.043	852.057
	fuel consumption, equivalent, t.c.f.		883	976	383	175	361	628	3406
	H_2O consumption for feeding	circulating, thousand t	19.15	19.53	13.13	12.61	12.62	16.05	93.09
		softened, t	-102.0	79.8	173.0	76.3	163.0	156.0	546.1
	harmful emissions	CO_2, t	1414	1561	613	280	578	1005	5451
		NO_x, t	7.415	8.189	3.214	1.468	3.033	4.762	28.081
Change in costs from AHP integration	from electricity sales, thousand USD		+111.00	-0.01	+0.01	+0.01	+0.01	-0.01	+111.01
	for fuel purchase, thousand USD		-273	-302	-119	-54,8	-112	-194	-1054.8
	H_2O for feeding	circulating, thousand USD	-3.83	-3.91	-2.63	-2.52	-2.52	-3.31	-18.72
		softened, thousand USD	1.02	-0.80	-1.73	-1.63	-1.63	-1.56	-6.33
	to pay the tax for harmful emissions	CO_2, thousand USD	-1.140	-1.260	-0.490	-0.230	-0.466	-0.810	-4.396
		NO_x, thousand USD	-0.510	-0.570	-0.222	-0.100	-0.209	-0.330	-1.941
		sum, thousand USD	-1.650	-1.830	-0.715	-0.330	-0.675	-1.140	-6.340
	Financial savings per month, thousand USD*		366.20	286.40	100.70	36.11	93.61	177.60	1060.62

* Total fixed monthly costs are $Ex_{\Sigma}/12 \approx 23.5$ thousand USD/month.

When $G_{\text{rw}} \geq 1650$ t/h $G_{\text{steam}}^{\text{cons}} = 15–45$ t/h and 17.3 MW$< Q_{\text{AHP}}^{\text{nom}} <$20 MW, as can be seen from Fig. 9, the payback period of AHP does not exceed 3 years, which indicates good prospects for the implementation of heat pump unit. As a result, guided by estimates based on discounting financial flows over time, it was adopted that $Q_{\text{AHP}}^{\text{nom opt}} = 20$ MW. During the discounting calculation period $\tau_{\text{calc}} = 30$ years (warranty period of AHP operation) difference in profit by options $Q_{\text{AHP}}^{\text{nom opt}}$ 17.3 MW and 20 MW in favor of higher capacity amounted to ~1 million USD ($G_{\text{steam}}^{\text{cons}} = 15$ t/h, $G_{\text{rw}} = 1700$ t/h, investor payments 4%).

The results of calculating the change in PT-60 performance indicators after integrating AHP 20 MW for each month and for the heating period as a whole are shown in Table 1. The table shows that the lower the outdoor air temperature t_{oa}^{i} is, the higher the monthly profit from the use of AHP. The total profit for the heating period was ~1061 thousand USD.

Integration of optimal power of AHP $Q_{\text{AHP}}^{\text{nom opt}} = 20$ MW in the PT-60 thermal scheme when working with $G_{\text{steam}}^{\text{cons}} = 15$ t/h, $G_{\text{rw}} = 1600$ t/h in a mode close to the thermal load (with partially open rotary diaphragm, heating selection pressure regulator turned on), with a fixed (except January) "useful" electricity generation leads to savings during the heating season: fuel by 3.48%, technical water for feeding the circulation system by 79.9%, softened water for feeding the turbine unit by 8.5%.

During the heating season, there is a reduction in harmful emissions into the atmosphere: CO_2 per ~5451 t, NO_x per ~28.08 t, which, along with saving 93.09 thousand tons of water, is a tangible environmental effect of the integration of AHP.

Conclusions

1. Using the example of the PT-60/70-130/13 steam turbine, the problem of determining the optimal nominal (declared by the manufacturer) thermal power of an integrated AHP with steam heating when operating in a mode with a partially open regulating diaphragm (steam consumption in the condenser $G_{\text{c}} \leq 50$ t/h). A new formulation of this optimization problem is presented, in which for the first time the approximate mathematical model of the AHP is highlighted, the objective function (the maximum is sought) is the monthly fuel savings after the pump integration. The general optimization problem, based on the average monthly outdoor temperature during the heating season in Ukraine, was divided into six auxiliary optimization problems. The optimal nominal thermal power of the AHP, taking into account discounting in time, was determined at 20 MW. At a given thermal load, the integration of the AHP leads to fuel savings, the volume of water used, and a reduction in harmful emissions of heat and greenhouse gases into the atmosphere.
2. The options for integrating the AHP heated by steam from the PT-60/70-130/13 production selection with a pressure of 1.286 MPa were calculated. Which forces the installation of a recycling expansion machine for energy saving and leads to an increase in investments. In the case of a lower pressure of steam released from the mentioned selection, the payback period of the studied energy-saving technology will probably decrease. Verification of this statement may be the subject of a separate study.
3. It is shown for the first time that, taking into account the change in average monthly outdoor temperatures for the climatic conditions of Ukraine, the integration of AHP with steam heating with a thermal capacity of 20 MW into a PT-60/70-130/13 steam turbine operating during the heating period with a significant thermal load (steam in the production selection is released to the consumer at 15–45 t/h, network water for heating is ~1650 t/h) with a steam consumption in the condenser up to 50 t/h is a promising energy-saving solution with a payback period of ~3 years (fuel cost is 300 USD/t.c.f., cost of electricity is 0.13 USD/(kWh)). At the same time, there is no difference between the "useful" generation of a turbine with and without AHP except in January, when this cannot be achieved due to non-fulfillment of the condition 26 t/h$\leq G_{\text{c}} \leq$50 t/h, which characterizes the degree of opening of the rotary diaphragm.
4. According to preliminary estimates, the integration of AHP 20 MW into PT-60/70-130/13, along with the saving of 93.09 thousand tons of technical water during the heating period, ensures a reduction in harmful emissions from the CHPP into the atmosphere: heat from circulating water by 85.94 GW·h (utilized by the heat pump unit), greenhouse gases by 3.48%. Natural gas was chosen as the fuel.

From the data provided, it is clear that the integration of AHP with steam heating into the steam turbine plant has a positive effect on the climate. Climate change is one of the main global problems that concern the world community. A comprehensive assessment of the impact of integrating AHP into a steam turbine on improving the climate, taking into account the use of different fuels, should be considered relevant. In our opinion, it has not yet found a worthy reflection.

5. Comparison of the results of the paper [20] and this study (with the same heat load and energy prices) shows that the operation of PT-60/70-130/13 with AHP 17.3 MW $G_{\mathrm{steam}}^{\mathrm{cons}}$=15 t/h, G_{rw}=1600 t/h with a closed rotary diaphragm due to greater fuel savings (~6%) with lower electricity generation leads to better economic indicators (profit for the heating season is 1257 thousand USD) compared to the option with a partially open diaphragm (similar profit is ~1011 thousand USD). This new study result was obtained during detailed modeling of thermal processes in an integrated turbine plant.

6. When using a steam utilization expansion machine and a small G_{c}, it is first necessary to note such a feature of the functioning of a highly loaded "PT" steam turbine integrated with an AHP with steam heating as the "annual generation bias" compared to the operation option without heat pump unit, since at low outdoor temperatures (-2.5 ºC and below) there is additional electricity generation and its reduction in the warm season, which contributes to the operation of the power system to ensure the annual schedule of electricity consumption.

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Оптимальна теплова потужність абсорбційного теплового насосу з паровим обігрівом, що інтегрований в парову турбіну ПТ-60/70-130/13

О. Л. Шубенко, В. О. Тарасова, М. Ю. Бабак, О. Ю. Бояршинов

Інститут енергетичних машин і систем ім. А. М. Підгорного НАН України,
61046, Україна, м. Харків, вул. Комунальників, 2/10

Сформульована і вирішена задача з визначення оптимальної теплової потужності абсорбційного бромісто-літієвого теплового насоса (АБТН) з паровим обігрівом, інтегрованого в теплову схему парової турбіни ПТ-60/70-130/13 при роботі на режимі з незначним відкриттям поворотної регулюючої діафрагми. Турбоустановка відпускала пару користувачам і забезпечувала теплопостачання за графіком 150 / 70 ºС. Характеристики АБТН моделювалися з використанням апроксимаційних залежностей, заснованих на характеристиках виробників термотрансформаторів. АБТН обігрівався парою з виробничого відбору турбіни після парової гвинтової машини, встановленої для енергозбереження. Загальна оптимізаційна задача з функцією цілі сумарні зміни місячних витрат палива після інтеграції АБТН, виходячи з середньомісячної температури зовнішнього повітря в опалювальному сезоні в Україні, розбивалася на 6 допоміжних оптимізаційних задач. Параметрами управління цих задач виступали: теплова потужність АБТН, тиск пари у конденсаторі турбіни і на вході у тепловий насос, витрата пари в голову турбіни. Дана задача вирішувалася методом покоординатного спуску. Досліджувалися режими з витратами пари у виробничий відбір турбіни споживачам: 15, 30 і 45 т/год. (з параметрами: 1,296 МПа, 280 ºС) і сітьової води: 1600, 1650 і 1700 м^3/год. Їх особливість – забезпечення «корисної» генерації в об'ємах, що відповідають роботі ПТ-60/70-130/13 без АБТН із закритою поворотною діафрагмою. Для всіх розглянутих варіантів навантаження турбіни оптимальна потужність інтегрованого АБТН визначена в 20 МВт. За опалювальний період ПТ-60/70-130/13 з АБТН 20 МВт при роботі на режимі, близькому до теплового навантаження при менших за досліджені витрати виробничої пари та сітьової води, дозволяє зекономити: палива ~3,5%, пом'якшеної води 8,5%, технічної води 79,9%, а також дає помітний екологічний ефект за рахунок зменшення шкідливих викидів до атмосфери. Попередній строк окупності АБТН близький до 3 років. Відзначається, що варіант роботи інтегрованої турбіни з частково відкритою регулюючою діафрагмою за наявних цін на паливо та електроенергію програє по економічних показниках варіанту із закритою діафрагмою.

Ключові слова*: енергозбереження, абсорбційний тепловий насос, теплова схема парової турбіни.*

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