Efficiency of using heat pumps with various refrigerants in real steam turbine power units with PT-80 and T-250 turbines

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Abstract. Prospects for increasing the efficiency of heat and electric energy-generation and heat-and-power supply at thermal power plants obviously draw attention to such modern and innovative technologies as heat pumps. Heat pumps allow efficient redistribution of energy flows. The abundance of low-potential heat carriers and heat sources in the cycle arrangement of the thermal power plants operation requires modernization of production and increase of the fuel heat utilization factor, therefore, reduction of specific fuel consumption for the production of heat and electricity. This paper analyzes the influence and practicability of introducing heat pumps into the heating circuit of the return water of the heat network of power units with PT-80 and T-250 turbines. Heat pumps of various configurations provide invariant energy conversion factor and efficiency. To assess energy and economic efficiency, modeling of the operation of power units and calculation of heat pump circuits for various refrigerants are performed. The economic effect is represented in quarterly cash savings of operating costs.

1 Introduction

Energy efficiency of manufacturing is the key issue of qualitative changes, that is, optimization and modernization of the industry, especially in conditions of energy intensity of products. Quantitatively, this is expressed in a decrease of specific costs of the reference fuel for electricity generation and heat supply [1], as applied to thermal power plants (TPP). One of the ways to realize this strategy is to use facilities, which allow utilizing underutilized (discharged) heat and then returning it to the cycle; an example of such a facility is a heat pump (HP). HPs have been used in practice abroad for more than half a century [2,3,4], but they still have not found wide distribution in the Russian Federation due to the cheapness of energy resources and “conservative” approaches in relation to the heat-and-power supply. The issue of introducing HP into TPP at different times was dealt with by V.P. Protsenko [5-7], E.E. Shpilrayn [8], A.I. Andryushchenko [9-11], V.M. Borovkov [12-14] etc. Despite all the prospects and advantages of using HPs in the heating cycle, the question of their influence on the operating modes of equipment and TTP in general requires additional researches.

The purpose of the work is to analyze the effect of the inclusion of vapor-compression HPs in the heating circuit of the reverse network water of the heat distribution system on the operation of power units with PT-80 and T-250 turbines and the selection of the optimal working fluids (refrigerant).

To achieve the goal it is necessary:
1. to propose circuit solutions for including HP for heating reverse network water (RNW);
2. to create simulation models of real power units with PT-80 and T-250 turbines without HP and with HP integrated;
3. to analyze the efficiency of the inclusion of three schemes of HP for heating the RNW: the simple scheme (without a regenerative heat exchanger (RHE)), with a RHE and with a RHE and a supercooler (SC) for a typical winter mode of operation with low heating loads;
4. to compare the efficiency of the HP in the heating circuits for the return network water of steam turbine power units with the PT-80 and T-250 turbines for various working fluids (refrigerants);
5. to analyze the impact of the inclusion of HP on the efficiency of steam turbine plants (STP).

2 Methods

An analysis of the influence of HP on the operation modes of the CHPP was carried out by means of simulation methods using CAD system «United Cycle» (Russia). It uses an algorithm that allows to use the parameters of one basic option to determine the characteristics of power plants with technological schemes of any complexity for various stationary operating modes of the main and auxiliary equipment [15-17]. CAD «United Cycle» is used by designers,
operating entities and in the work of such companies as PJSC «Power Machines» and PJSC «TGK-1», etc.

The use of a HP in a heating system (heating of RNW) and its effect on the operating modes of power units and thermal power plants are considered using cycle arrangements of a mathematical model of power units with PT-80 and T-250 turbines as examples.

For simulation mathematical modeling of power units, data is received from catalogs of manufacturers of basic power facilities, in particular, STP. The main mode of operation, in which the HP is included and the core attributes are compared is the winter mode with low heating loads, being the most characteristic for the North-West region of the Russia.

Figure 1 shows the cycle arrangement of a power unit with a T-250 turbine without HP.

The source of low-potential heat (LPH) for the HP is cooling water at the outlet of the condenser of a steam turbine. The connection scheme of the heat pump installation to the pipeline supplying RNW to the heating network to line heaters of power units (Fig. 2) is optimal, since it takes into account the features of the heating system and is suitable for both closed and open heat supply systems.

The way of realization of the heat that is released during the operation of TPP must be determined by current need of a particular TPP in real conditions. The way of using the heat obtained by inclusion and operation of HP as part of the TPP has the crucial nature. The option of using heat from HP to increase the total heat output from TPP (the total the electric load of the TPP and the total consumption of burned fuel remain unchanged) is the easiest variant in relation to the modernization and economical in relation to the capital costs[18].
In this work, the vapor compression heat pump is integrated in three layouts: without modifications (simple scheme), with a RHE, with a RHE and SC.

In the real cycle of heat pumps, RHE allows to achieve a refrigerant’s supercooling at the inlet to the throttle, that increases its efficiency, as well as overheating the refrigerant vapor after the evaporator increases the compressor’s efficiency. HP of medium power level, as a rule, are supplemented by RHE, which reduce the additional expenses for compressor drive (own needs); high-performance HPs are modified by RHE and SC for a deep cooling of refrigerants and increase the heat transfer efficiency.

Table 1. Initial data for calculating the operating modes of power units without HP.

| Parameter                          | PT-80 | T-250 |
|------------------------------------|-------|-------|
| Electricity supplied, MW           | 79.73 | 253.43|
| Heat supplied, MW                  | 72.57 | 311.06|
| Boiler unit power, MW (specific calorific value 29.903 MJ/kg) | 250.48 | 686.08 |

Technical calculations were made for HP with a fixed heat release $Q_{hp}=13$ MW.

The working fluid – the refrigerant – is an extremely important element of the operation of HP [18-24]. The choice of refrigerant is often made for various reasons:
1. safety of use, both technical and environmental;
2. flexibility of the parameters of the possible operation of the refrigerant;
3. cost;
4. use efficiency.

Table 2. Initial data for the calculation of HP.

| Parameter                          | PT-80 | T-250 |
|------------------------------------|-------|-------|
| Heat pump power, MW               | 13    | 13    |
| Cooling water consumption, kg/s    | 417   | 1945  |
| LPH’s temperature before HP, °C    | 31.9  | 27.6  |
| LPH’s temperature after HP, °C     | 25    | 25    |
| RNW’s temperature before HP, °C    | 57    | 63    |
| Ambient temperature, °C            | 0     | 0     |

Since for the energy sector, from a technical point of view, the chief criterion for choosing a refrigerant is its efficiency, the brands of refrigerants of different hazard groups most used in industry today are compared:
1. R12 – freon of the hazard group "A", causes significant depletion of the ozone layer;
2. R22 – freon of hazard group “B”, causes weak depletion of the ozone layer;
3. R134a – freon of the hazard group “C”, does not cause efforts on the ozone layer It’s an ozone-safe freon.

Recently freon R12 was the most popular and widespread, however, due to its belonging to ozonohazardous substances, there is a massive and widespread rejection of this brand of refrigerant in favor of, in most cases, freon R134a. Freon R22 is taken to represent an intermediate hazard group.

Energy conversion coefficient (ECC) for the simple HP:

$$\mu = \frac{0.98 \frac{273 + t_1}{273 + t_1} (h_1 - h_t) + (h_2 - h_t)}{h_2 - h_t},$$

(1)

where: $t_1$ – ambient temperature, °C;
$\eta_c$ – refrigerant condensation temperature, °C.

Compressor’s power, MW:

$$N_c = \frac{Q_{hp}}{\eta_c \cdot \eta_e \cdot \frac{273 + t_1}{273 + t_1} (h_2 - h_t) + (h_2 - h_t)}.$$ 

(2)

where: $\eta_c$ and $\eta_e$ – mechanical and electrical efficiency of the compressor’s motor (taken equal to 0.95 and 0.9, respectively);

$Q_{hp}$ – heat pump power, MW.

Low-potential source flow through the evaporator, t/h:

$$G_{LPS} = \frac{Q_{hp}}{c_p \cdot (t_{l_{wp}} - t_{lp}) \cdot (h_2 - h_t)}.$$ 

(3)

where: $c_p$ – heat capacity of LPS, kJ/kg/°C;
$t_{lp1}$ – LPS temperature before HP, °C;
$t_{lp2}$ – LPS temperature after HP, °C.

It is worth comparing the efficiency of HP’s operation with various refrigerants by ECC, characterizing the process of heat transfer by the heat pump from the LPS to the reverse water of the heat network (consumer), as well as by the value of the HP’s own needs, expressed mainly by the capacity (power consumption) of the HP’s compressor.

3 Results and Discussion

Due to the fact that the efficiency of HP without modifications (1), with RHE (2) and with RHE and SC (3) is determined by the temperature difference between the source and consumer, as well as the flow rate of the coolant (network water), the efficiency of the HP on various refrigerants for power units with PT-80 and T-250 turbines may vary, as can be seen from table 3.

Table 3. The values of ECC and the compressor power values for HP with various refrigerants.

| Refrigerant | PT-80  | T-250  |  |  |
|-------------|--------|--------|  |  |
| ECC        | Nc, MW | 1 2 3 | 1 2 3 | 1 2 3 |
| R12        | 4 4 4 | 3 3 3 | 2 2 2 | 1 1 1 |
| R22        | 4 4 4 | 3 3 3 | 2 2 2 | 1 1 1 |
| R134a      | 4 4 4 | 3 3 3 | 2 2 2 | 1 1 1 |
The main indicators of the efficiency of TTP are specific fuel consumptions for the production of thermal and electrical energy. The values of specific fuel consumption are graphically presented (Fig. 3, 4):

![Fig. 3. Specific fuel consumption for the production of electric and thermal energy for a power unit with a turbine PT-80 without and with the inclusion of HP with RHE and SC (R134a) in the heating circuit of the return network water of the heating network.](image)

Because of the constant level of HP power the specific fuel consumption for the production of heat energy is constant for each option of HP (simple HP, HP with RHE, HP with RHE and SC) and refrigerants (R12, R22, R134a) and are 104.12 g/(kW∙h) and 117.91 g/(kW∙h) for power units with PT-80 and T-250 turbines, respectively.

![Fig. 4. Specific fuel consumption for the production of electric and heat energy for a power unit with a turbine T-250 without and with the inclusion of HP with RHE and SC (R134a) in the heating circuit of the return network water of the heating network.](image)

The results of calculations of specific fuel consumption for the production of heat and electric energy for power units with turbines PT-80 and T-250 are presented in table 5.

| Parameter                  | PT-80 | T-250 |
|----------------------------|-------|-------|
| Electricity supplied, MW   | 79.73 | 253.43|
| Heat supplied, MW          | 85.57 | 324.06|
| Boiler unit power, MW      | 250.48| 686.08|
| (specific calorific value  |       |       |
| 29.903 MJ/kg)             |       |       |
| HP power, MW               | 13    | 13    |
| Compressor power, MW       | 3.5   | 3.49  |

The results of calculations of specific fuel consumption for the production of heat and electric energy for power units with PT-80 and T-250 turbines with inclusion HP (simple HP = 1, HP with RHE = 2, HP with RHE and SC = 3) in the system of heating RNW for various refrigerants (R12, R22, R134a) are presented in table 6.

| Refrigerants | Spec. fuel consumption for h/e, g/(kW·h) | Spec. fuel consumption for e/e, g/(kW·h) |
|--------------|----------------------------------------|----------------------------------------|
| R12          | 27                                     | 19                                     |
| R22          | 27                                     | 19                                     |
| R13          | 27                                     | 19                                     |

The economic effect of modernization of the heating system (heating of the return network water) was calculated based on the ratio of the proceeds from the operation of the heat pump unit (heat supply) and the corresponding costs of electricity for the compressor’s motor (an increase of own needs means an increase of specific fuel consumption for the production of electric energy) [25-29]. Computations were made using energy tariffs (heat and electricity) for PJSC “TGK-1” in 2019 (formula 4).

The positive economic effect of the introduction of HP is determined by the formula:

\[ PEE = \Delta Q_H C_T - \Delta E_{ON} C_{ON}, \]  

where: \( \Delta Q_H \) – increment of heat as a result of the introduction of HP, MW; \( \Delta E_{ON} \) – increase in electricity costs for own needs as a result of the introduction of HPP, MW; \( C_T \) – tariff cost of thermal energy for vacation, rubles/MW; \( C_{ON} \) – tariff value of electric energy for own needs, rubles/MW.
Table 7. Quarterly money savings for various options of modifying the reverse heating water heating schemes by integrating HP.

| Money savings, million rubles/quarter | PT-80 | T-250 |
|--------------------------------------|-------|-------|
|                                      | 1     | 2     | 3     | 1     | 2     | 3     |
| R12                                 | 7.67  | 7.79  | 9.64  | 7.72  | 7.82  | 9.87  |
| R22                                 | 7.48  | 7.51  | 9.29  | 7.39  | 7.41  | 9.43  |
| R134a                               | 7.32  | 7.43  | 9.54  | 7.21  | 7.45  | 9.79  |

The economic benefit of the introduction of these three options in the heating system for the return network water of power units with PT-80 and T-250 turbines was calculated according to operational characteristics, excluding capital costs, risks and depreciation charges [30-35].

4 Conclusions

According to the results of mathematical simulation performed by the CAD system «United Cycles» of real cycle arrangements of power units with PT-80 and T-250 turbines and upgraded with heat pumps, including HP with RHE, with RHE and SC, integrated in a heating system for reverse network water with various refrigerants there was determined the most effective mode; the economic feasibility of such events was also analyzed.

Analysis of the inclusion of HP’s influence on the operation mode of real STP showed the advantage of the scheme with a high-power heat pump (heat output 13 MW) with a regenerative heat exchanger and supercooler for additional heat production. This scheme allows to save about 9.54 and 9.79 million rubles per quarter for power units with PT-80 and T-250 turbines, respectively, while operating with the becoming more popular ozone-friendly freon R134a.

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