The use of heat pump installations as part of waste energy conversion complexes in the joint generation of electrical and thermal energy

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Abstract. The possibility of using heat pump installations at thermal power plants is considered. An estimation of the sources of low-potential heat for the operation of the heat pump in the joint generation of electrical and thermal energy was carried out. The results of a comparative analysis of the schemes for the inclusion of a heat pump in the cooling system of recycled water are presented using the example of the Kirov thermal power plant.

1. Introduction

The priority direction in the policy of energy saving is the development of energy-saving technologies aimed at the utilization of heat of secondary energy resources – thermal waste of power plants, industrial production, municipal, domestic, residential facilities.

As follows from the second law of thermodynamics, it is impossible to turn all the heat supplied to the working body in the heat-power cycle into work, since part of the heat supplied will need to be taken to a cold source. The task of energy-saving technology is that before giving the environment this waste energy, it is necessary to take the maximum amount of remaining exergy and use it with due efficiency [1].

The maximum use of the exergy of low-potential secondary energy sources will allow the heat pump installation. The experience of introducing heat pump plants into heat and technological schemes of chemical, oil-refining, food, pulp and paper industries is well known [2-5]. With the removal of heat from low-potential sources and the expenditure of mechanical energy, they receive heat with a temperature at which it can be used for heating, hot water and for technology. The most favorable conditions for the use of heat pumps for the simultaneous reception of heat and cold, where the ratio of demand for them is close to the ratio of heat output of the heat pump cycle and cooling capacity.

The main sources of low-potential heat in the joint generation of electrical and thermal energy are:

- heat of cooling systems with water of the equipment of thermal power plant (TPP), state district power station;
- condensate heat from schemes of continuous blowdown expanders;
- secondary waste heat of the reverse network water.

The combined production of electric and thermal energy at steam turbine TPPs, which allowed to save substantially fuel and energy resources of the country during the Soviet period, is currently not effective enough. One of the main reasons for the reduction in the efficiency of the TPP is a significant reduction in the generation of electricity by thermal consumption [6].
A hidden reserve of improving the energy efficiency of the stations are the cooling systems of steam turbine condensers of TPP. Thermal power plants consume a significant amount of water to condense steam in condensers of steam turbines, provided by technical water supply. Two schemes of organization of technical water supply for cooling steam turbine condensers are most common: co-current water taken from a river passes through turbine condensers and then merges back downstream and circulating with repeated use of water after cooling it in cooling towers or splashing pool. However, both schemes of cooling the condensers of steam turbines are associated with large losses of thermal energy to the environment, which leads to a decrease in the efficiency of the TPP, an increase in the degree of negative impact on the environment.

Improvement of the cooling system is possible due to the introduction of a heat pump unit, which will allow taking heat from the cooling water turbine heated in the condenser, increasing its potential and using it for the own needs of the TPP [7-8]. It's also possible in heat pump systems to use the heat of the so-called "dirty" condensate from the scheme of the continuous blowdown of boiler units, which due to the salt content is unsuitable for return to the cycle of the station is useless and is discharged into the hydro-, ash removal system.

2. Object of research
The object of research is one of the thermal power plant of the city of Kirov with a total thermal capacity of 1600 MW with installed electric power of 320 MW [9]. Six turbines are installed at the plant: one IIT-60/75-130/13, one IIT-60-130/13 and four T-50-130. To provide cooling of condensers of turbines on the territory of the power plant, there are 4 typical counterflow cooling towers. Cooling water is used at the power plant according to the circulating scheme. From the collector by circulating electric pumps it is supplied respectively to the condensers of turbogenerators. At the first stage, turbogenerators use pumps with a capacity of 6300 m3/h and 5000 m3/h. After the condensers, the heated water enters the cooling tower, from where it returns to the circulation collector. In the summer, three cooling towers operate, the cooling water flow rate in the circulation circuit reaches 28000-30000 m3/h, in the autumn-winter period there is one cooling tower in operation with a flow rate close to the nominal flow of 12000-14000 m3/h.

As a result of the analysis of the characteristics of the main equipment of the TPP, it was revealed that:
- a significant amount of heat in the TPP is lost - discharged into the atmosphere in the cooling towers. So, for example, for a single turbine T-50-130, even when operating in the most efficient combined mode with a fully closed diaphragm of a low-pressure cylinder, the standard venting discharge of steam into the condenser is 10 t/h or 6,88 MW;
- a large amount of thermal energy is spent on heating the complex of industrial and administrative buildings of the enterprise. The share of own heating needs in relation to the release of thermal energy during the heating period 2016-2017 was 2,1 %;
- to ensure the cost of these coolants expends electrical energy. The share of the expense for own needs in relation to the expenditure on leave during the heating period 2016-2017 was 8,2 %.

As can be seen from the presented data, the thermal power plant under consideration has a significant potential for the use of low-potential heat of the cooling water of the circulating circuit. Thus, as a source of low-potential heat at the considered TPP selected water flow with low temperature – the flow of recycled water. The received heat energy is proposed to be used for the heating system of industrial buildings of the same CHP, namely for heating the boiler compartment of the main building.

The proposed scheme for using a heat pump (HP) is shown in Figure 1. Here, the condensate after the turbine condensers 23, previously directed to the cooling tower 36, is proposed to be partially redirected to the evaporator of the heat pump. In the evaporator (Figure 1), the condensate is cooled to a temperature corresponding to the temperature of the cooled water in the cooling tower and is then directed to the return line of the circulating water supply.

The thermal potential of the condensate in the heat pump is increased by the compression of the refrigerant vapor, which received heat from the condensate flow. The increased heat potential of the
flow is transferred to the heat pump condenser where the heat transfer to the consumer is due to the refrigerant condensation.

**Figure 1.** The scheme of the TPP with the inclusion of a heat pump: 1 – boiler unit, 2 - furnace shields, 3 - lowering pipes, 4 - drum of the boiler, 5 - air heater, 6 - water economizer, 7 - I and II stages of supersteamheater, 8 - intermediate superheater, 9 - 10 - burner, 11 - train with coal, 12 - coal storage, 13 - coal transportation and primary crushing system, 14 - raw bunker, 15 - mill, 16 - ash collector, 17 - smoke exhaust, 18 - chimney , 19-electric generator, 20-turbo installation, 21-cylinders of high, medium and low 22 - condensate pump, 24.27 - regenerative heaters of low and high pressure, 25 - deaerator, 26 - feed pump, 28 - water heaters I and II stages, 29.30 - water supply pumps I and II stages, 31 - hydraulic ash removal channel, 32 - shoal pump, 33 - ash dump, 34 - clarified water pump, 35 - circulating water pump, 36 - cooling tower, 37 - power generator, 38 - generator exciter, 39 - boosting transformer.

### 3. Results

The calculation of the heat pump system for heating the 1-st stage of the boiler section of the main building of the Kirov TPP plant in the winter period as a basic source of heat has been made. The source of low-potential heat is a circulation system with a cooling water flow rate up to 21000 m3/h and an average annual temperature of 28 °C.

The following were taken as input data (Table 1).

#### Table 1. Initial data for the calculation of the heat pump installation.

| №  | Parameter                                                                 | Value | Unit |
|----|---------------------------------------------------------------------------|-------|------|
| 1  | The thermal load $Q_{TH}$ for the boiler room building as a heated heat pump unit | 1731  | KW   |
| 2  | The temperature of the low-potential heat carrier of the direct circulating water after the condenser to the cooling tower at the entrance to the heat pump $t_{TH1}$ | 28    | °C   |
| 3  | The temperature of the low-potential flow of return circulating water for cooling into the turbine condenser after the heat pump $t_{TH2}$ | 22    | °C   |
| 4  | The temperature of the high-potential flow at the inlet to the heat pump of the heating system $t_{BH}$ | 42    | °C   |
| 5  | The temperature of the hot water after the heat pump – the direct line of the heating system according to the temperature schedule $t_{OH}$ | 55    | °C   |
| 6  | Average ambient temperature during the heating season $t_0$               | 5,4   | °C   |
Temperature of superheating of steam in the intermediate heat exchanger $\Delta t = 20$ °C

Three schemes of switching the heat pump into the cooling system of the circulating water of the TPP are calculated: 1 - a classical steam compression heat pump [10]; 2 - scheme with an intermediate heat exchanger (supercooling of liquid and superheating of steam is combined in an additional intermediate heat exchanger, where the hot freon after the condenser heats the cold freon after the evaporator); 3 - scheme with an intermediate heat exchanger and a subcooler (if a hot heat carrier is produced for water supply, that is, it enters the inlet much colder than it leaves the heat pump, supercooling of the liquid is possible in an additional heat exchanger - subcooler, which is installed after the condenser).

Energy efficiency indicators are summarized in Table 2. As can be seen from the table, the highest coefficient of conversion of heat and electricity, as well as the lowest consumption of primary fuel - in scheme No. 3. By increasing the consumed power by 13.85 kJ/kg, the thermal load in schemes No. 2 and 3 increases by 33 and 57.5 kJ/kg, respectively, which leads to an increase in the heat conversion coefficient $\mu$. Since the exergy of electricity is equal to the amount of electricity, and the exergy of the heat carrier makes up only a part of its heat, this leads to loss of exergy and a decrease in the exergy efficiency for scheme No. 2.

Table 2. Indicators of the energy efficiency of the calculated options.

| No scheme | 1   | 2   | 3   |
|----------|-----|-----|-----|
| Specific heat load of the heat pump, kJ/kg | 264,9 | 297,9 | 322,4 |
| Specific energy consumed by the electric motor, kJ/kg | 68,95 | 82,8 |
| Degree of compression in the compressor | 3,48 |
| Conversion factor of heat | 5,05 | 4,74 | 5,12 |
| Coefficient of electricity conversion | 3,84 | 3,6 | 3,89 |
| Specific consumption of primary energy | 0,68 | 0,73 | 0,68 |
| Exergy efficiency | 0,389 | 0,371 | 0,506 |

Based on the results presented in Table 2, Scheme No. 3 was chosen. The cycle of the heat pump system for the selected option is presented in the form of the $p, h$-diagram in Figure 2.

The cost-effectiveness of introducing HP is shown in Table 3.

Figure 2. Cycle of heat pump system with intermediate heat exchanger and subcooler
Selected heat pump unit HT-3000 with heat recovery and supercooler, designed and selected the main equipment for the heat pump installation – capacitor brand 1000KHP-1,6.
To assess the economic efficiency, a feasibility study of the introduction of a heat pump installation was carried out, the payback period of the main equipment was determined, which amounted to about 5 years.

Table 3. Results of technical and economic calculation.

| Economic parameter                                | Year of operation |
|--------------------------------------------------|-------------------|
|                                                  | 1                | 2                | 3                | 4                | 5                | 6                | 7                |
| Income tax savings due to depreciation, th. p.   | 93,4             | 93,4             | 93,4             | 93,4             | 93,4             | 93,4             | 93,4             |
| Savings in heat supply from HP, th. p.           | 5336,45          | 5336,45          | 5336,45          | 5336,45          | 5336,45          | 5336,45          | 5336,45          |
| Operating costs, th. p.                          | 3220             | 3220             | 3220             | 3220             | 3220             | 3220             | 3220             |
| Net cash flow, th. p.                            | 2209,85          | 2209,85          | 2209,85          | 2209,85          | 2209,85          | 2209,85          | 2209,85          |
| Net cash flow cumulative total, th. p.           | -11684,00        | -9474,15         | -7264,30         | -5054,45         | -2844,60         | -634,75          | 1575,10          |

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