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The increasing of the energy efficiency of nuclear power plants with fast neutron reactors by utilizing waste heat using heat pumps

V S Kostarev, O L Tashlykov and V A Klimova

Department of Nuclear Power Plants and Renewable Energy Sources, Ural Federal University named after the first President of Russia B. N. Yeltsin, Mira St., 19, Yekaterinburg 620002, Russia

E-mail: slavakostarev@yandex.ru

Abstract. Today, an important task for the economy is to increase the efficiency of using primary fuel. At present, for nuclear power plants with VVER reactors, thermal efficiency is about 33%, with fast neutron reactors - more than 40%. This means that most of the heat produced is released into the atmosphere. In this paper, we consider methods to solve the problem of increasing energy efficiency by the example of NPPs with fast neutron reactors due to the utilization of low-grade waste heat. The results of practical implementation of utilization of low-potential thermal energy of thermal and nuclear power plants using heat pumps were generalized. The analysis of the utilization efficiency of waste heat from various NPP systems was performed.

1. Introduction

The creation of a competitive electric power market in Russia inevitably leads to the fact that energy companies are forced to look for new ways to improve the efficiency and cost-effectiveness of their activities. Therefore, today, the issue of developing new energy-saving technologies for the purpose of more efficient use of energy resources remains a pressing problem in the power industry of Russia.

Today, nuclear and thermal power plants constitute a large part of the energy system of Russia (about 67%). Therefore, in the operation of thermal power plants and nuclear power plants, it is necessary to take into account the factor of thermal pollution of the environment, which leads to significant environmental consequences, both on a local and a global scale. Reducing thermal discharges is an urgent task facing thermal and nuclear energy.

One of the possible ways to reduce thermal discharges from nuclear power plants is the use of heat pumps in the design of a steam turbine plant, which helps reduce environmental burden by cutting down thermal emissions from disposing of waste heat.

A heat pump is a thermodynamic installation in which heat from a low-potential source is transferred to the consumer at a higher temperature. This is done by mechanical work. The principle of operation of a heat pump is that the refrigerant evaporates in the chamber with low pressure and temperature and condenses in the chamber with high pressure and temperature, thereby transferring heat from a cold body to a heated one, that is, in a direction in which spontaneous heat exchange is impossible.

Heat of technological processes and industrial discharges can be used as a source of low-potential thermal energy. Low-grade heat can be transformed into sufficient for beneficial use heat by increas-

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ing the temperature of the medium with heat pumps. Such heat can be directed to internal and external consumers.

Several ways of heat pump inclusion in the scheme of steam turbine are described in the literature.

In [1] it is proposed to direct a part of the steam that has been exhausted in the turbine to the condenser, and to supply its' another part to the heat pump evaporator. Steam condensate after the turbine condenser enters the heat pump, where it is heated. Then it goes to the regenerative heating system. The network water returning from consumers is also heated with a heat pump. The basic flow diagram of the heat pump connection is shown in figure 1.

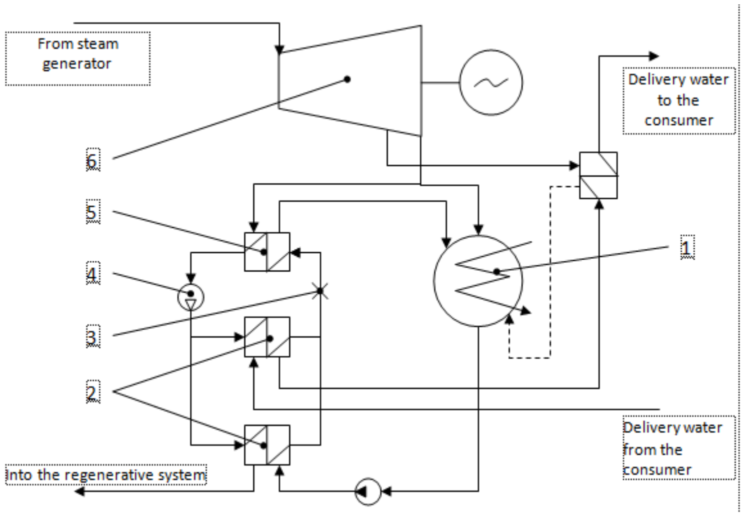

Figure 1. The basic flow diagram of connecting of the heat pump: 1 - turbine condenser, 2 - heat pump condensers, 3 - choke, 4 - compressor, 5 - heat pump evaporator, 6 – turbine

In [2], it is proposed to connect the heat pump evaporator directly to the set of turbine condenser tubes. Here, the operation of the heat pump is used to heat the network water. The basic flow diagram of the heat pump connection is shown in figure 2.

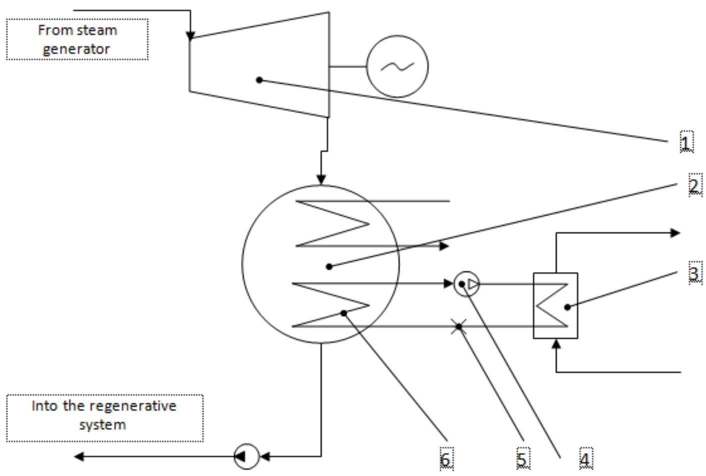

Figure 2. The basic flow diagram of connecting of the heat pump: 1 - turbine, 2 - turbine condenser, 3 - heat pump condenser, 4 - compressor, 5 - throttle, 6 - bundles of heat pump evaporator tubes

In the scheme proposed by the development team of South-Russian State Technical University, it is proposed to use the cooling water of a steam turbine condenser as a source of low-grade heat. Heat can be taken from both water entering the condenser inlet and water leaving the condenser. The heat pump is connected to the regenerative heating system and replaces the first low pressure heater. The basic flow diagram of the heat pump connection is shown in figure 3.

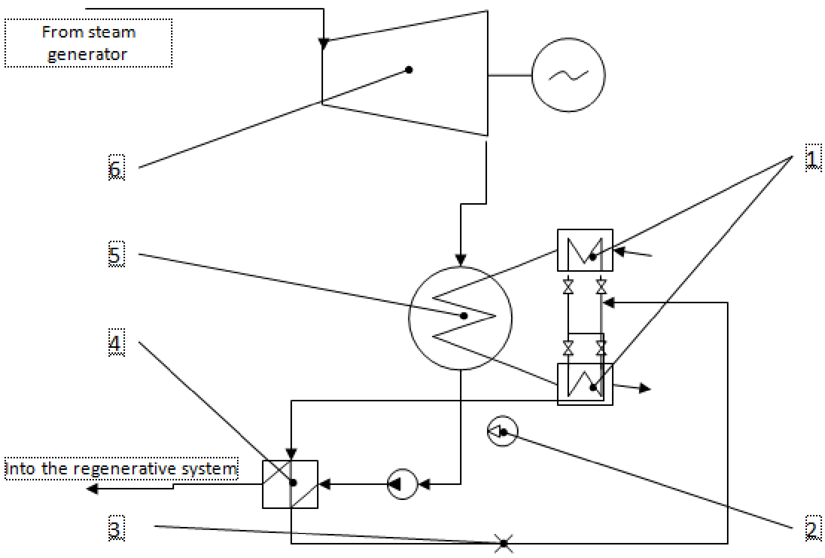

Figure 3. The basic flow diagram of connecting of the heat pump:
1 - heat pump evaporator, 2 - heat pump compressor, 3 - choke device,
4 - low pressure heater, 5 - turbine condenser, 6 - turbine

2. Materials and Methods

One of the currently considered modes of heat supply from nuclear power plants of settlements located at a considerable distance can be cited as an example of the use of heat pumps at nuclear power plants. The project of St. Petersburg heat supply from Leningrad NPP using adsorption heat pumps can significantly reduce the temperature and the pressure of the energy carrier during transportation, and bring them to the required by consumer near the places of heat consumption. The authors of this project state that using heat pumps only for heating purposes increases the revenue of a 1.2 GW NPP unit from 6 to 12 billion rubles per year with 16.2 million megawatt-hour of heat supplied per year depending on its cost in the region [3]. Also in the future of this project, it is supposed to grow microalgae in bioreactors with large-scale production of various bioproducts, including biofuels, by utilizing low-potential heat [4].

Consider the possibility of using heat pumps at nuclear power plants with fast neutron reactors. To date, thermal efficiency is 39.4% for BN-800 and 42.6% for BN-600, the remaining heat (about 60%) is irretrievably lost in the cooling system of the steam turbine condenser, i.e. discharged into the environment.

For a number of years, the research work has been carried out at UrFU to study ways to improve the energy efficiency of NPPs, including those with fast neutron reactors. In particular, in [5], [6], [7], [8], the results of an analysis of the possibility of using heat pumps and the possibility of utilizing low-grade heat for a BN-600 power unit with are presented. According to the results of these works, it was concluded that the use of heat pumps in the main condenser cooling circuit with the aim of improving the economic performance of the plant today is not economically justified, but its use reduces the thermal discharges of nuclear power plants. For a power unit with a BN-600 reactor, the reduction of thermal pollution was from 5 to 6%, depending on the season and the operation mode of the heat pump (figure 4) [5].

A variant was also proposed for heat pumps installing in a system of make-up water preparing for heat grids in Zarechny [5]. It was calculated that in case of installation of 3 heat pumps of 300 kW each (1 per loop), the net profit would be 2 845 888 rubles per year, with a 4.7 years payback period.

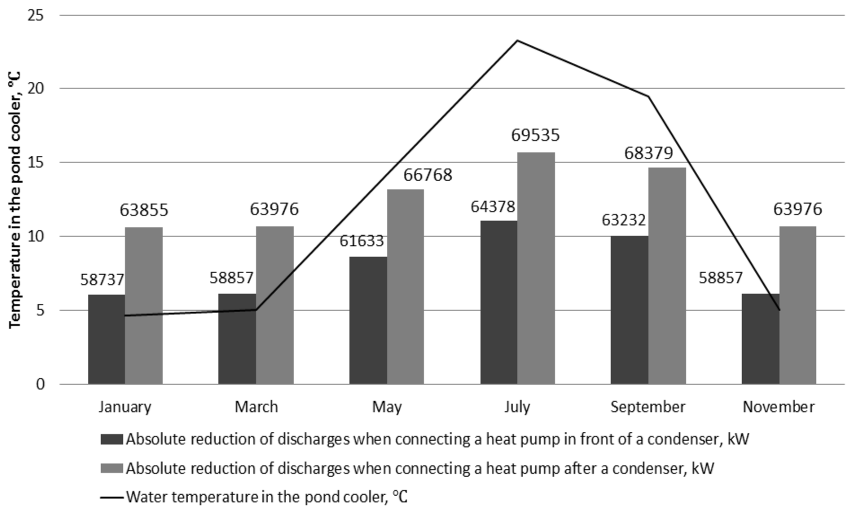

Figure 4. Absolute reduction of thermal discharges of a power unit with a BN-600 reactor.

The purpose of this work is to investigate the possibility of energy efficiency increasing of NPPs with fast neutron reactors due to the utilization of low-grade heat discharged from auxiliary systems.

The fourth power unit of Beloyarsk NPP with BN-800 reactor was considered as a possible source of low-grade heat.

Additional heat generated by heat pumps can be used on:

- heating of industrial and administrative-household NPP buildings;
- heating of water used for the heating and hot water supply systems of Zarechny.

The heat capacity consumed by industrial and administrative buildings of a nuclear power plant can reach several mega-watts. Heat consumers of a power unit with fast neutron reactor are shown in figure 5

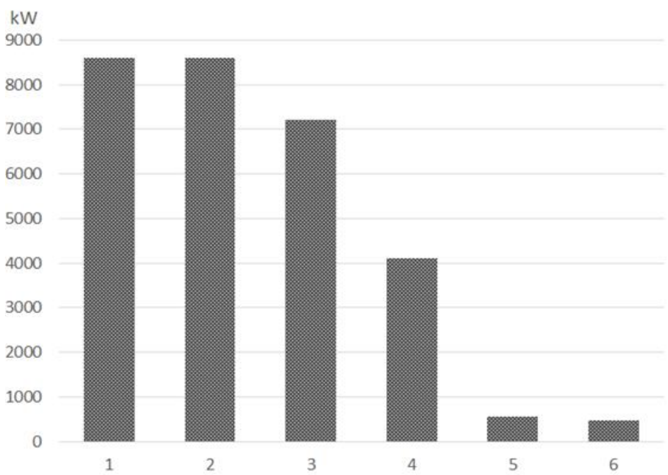

Figure 5. Heat consumers at Beloyarsk NPP: 1 - forced ventilation, air heating systems, etc. (computer room), 2 - inlet ventilation (room A), 3 - inlet ventilation (room B), 4 - inlet ventilation (room B), 5 - air curtains (railway corridor), 6 - other consumers. Designation of premises is conditional.

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Currently, heat for these consumers is taken from the turbine operating steam, which is economically unprofitable, while the utilization of waste heat using heat pumps can improve the plant's energy efficiency and reduce thermal pollution of the environment.

The calculation results are shown in figure 6. As a result of research, it was found that the most efficient possible source of heat is the cooling system of the stator winding of the generator (thermal power 14 905.1 kW with a temperature difference at the inlet and outlet 21.4 °C).

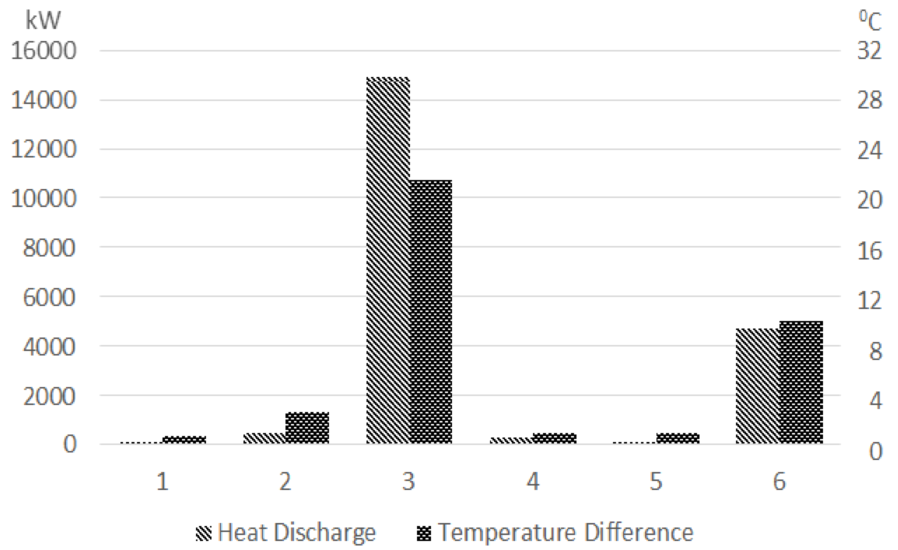

Figure 6. Heat discharges and temperature drops of the auxiliary systems of the BN-800 power unit: 1 - evaporator condenser of drainage expander, 2 - exciter air coolers, 3 - generator stator coil coolers, 4 - cooling of the main feed pumps PEN, 5 - cooling of the main upstream pumps PEN, 6 - cooler dirty condensate.

3. Results

Sources of low-grade heat at the BN-800 power unit are auxiliary systems cooled by an intermediate circuit. Data on possible sources of low potential heat are shown in table 1. Measurements of the parameters were carried out while the power unit was operating at rated power, using instruments at the location of the equipment, IVS, TX-5.11 thermal probe. Also data of design materials and [9] were used.

Table 1. Expenses of cooling water and temperature characteristics of some consumers of the industrial circuit system

Consumer name	Input / output temperature, °C	Number of working / standby units	Cooling water consumption, m^3/h
Drain expansion trap cooler	16,5/17,2	1	140
Causative air coolers	16,5/19,1	4	150 (4x37,5)
Generator stator coil coolers	16,5/37,9	1/1	600
Cooling of the main feed pumps PEN	17,1/18,1	3/1	262,4 (4x65,6)
Cooling upstream PEN feed pumps	17,4/18,3	3/1	105,6 (4x26,4)
Dirty condensate cooler	16,5/26,5	1	400

Calculations to determine thermal discharges were made according to the formula:

$$Q = G \cdot c_p \cdot (t_{inp} - t_{outp}), \tag{1}$$

where G is the flow rate of process water, c_p is the specific heat capacity of water, t_{inp} and t_{outp} are the inlet and outlet temperatures of the source, respectively.

4. Discussion

To increase the potential of industrial water, which removes heat from the coolers of the generator stator windings, it is proposed to use a heat pump that raises the temperature to 50-55 °C, which is sufficient for heating or hot water.

As the German experience shows, it is most efficient to use the rear heating with the help of heat pumps for underfloor heating. This experience can be used in the design of buildings under construction and design of NPP power units, including BN-1200.

Obviously, from the point of view of the production efficiency of electric and thermal energy, the use of heat pumps in auxiliary systems will be justified. According to preliminary calculations, when installing a single 1.5 MW heat pump with a BN-800 reactor into a thermal circuit of a power unit, the payback period will be about 4.8 years.

5. Conclusion

Thus, the use of heat pumps for low-grade heat utilizing at the BN-800 power unit has the following positive points:

- reduction of steam extraction from the thermal circuit of the unit, which leads to additional energy production at constant production costs;
- reduction of thermal emissions into the environment.

At present, work is underway on the design substantiation of the economic efficiency of utilization of the waste heat of the auxiliary systems of the NPP power unit with the BN-800 fast neutron reactor and the designed unit with the BN-1200 reactor.

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