Using refrigeration machines and heat pumps in the cycle of steam generator in agricultural industry

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Abstract. Chillers are required at all plant-processing plants. Refrigeration can be obtained from energy industry facilities. Absorption chillers are the most reliable units for use in thermal power plant cycles. Such units usually work in conjunction with heating networks and cooling systems of steam turbine power units. For example, in a heated water cooling system after a steam turbine condenser, absorption chillers are already in use. At the same time, the authors of the article offer another application of such aggregates. Low-power steam turbines use air cooling and water-air heat exchangers. In this cooling system, an absorption chiller can be used to increase the efficiency of the thermal power plant. Such chillers are highly reliable, so they must work until the end of the payback period of new equipment.

1. Introduction
The most common cooling systems for steam and gas turbines are hydrogen cooling systems. There are also air cooling systems. Mainly, application of a particular system depends on the purpose of the turbine and its power. For example, on block steam turbine plants with a capacity of more than 100 MW, only a hydrogen cooling system is used. While for turbines with less power it is quite acceptable to use air cooling. The disadvantage of air cooling is the low efficiency of the currently used circuits. The article will discuss options for improving the efficiency of cooling circuits. For example, the use of heated water for an absorption chiller or chiller cycle is a common technology for steam generators.

2. Scientific novelty
Air cooling of low-power steam turbine power generators is less effective than hydrogen cooling. However, when applying methods of additional energy generation in the form of heat, it is possible to increase the thermal efficiency of a thermal power plant. The authors propose the use of refrigeration machines and heat pumps in the cooling system of steam turbine power generators. At the moment, the most efficient ones are absorption chillers, as well as heat pumps in the ORC cycle.

Turbin generator ventilation is carried out in a closed-loop [1, 2]. Hydrogen circulation is provided by two fans installed on the rotor shaft. Hydrogen is cooled by gas coolers horizontally embedded in the stator housing [3, 4]. Thermal control of all main turbine generator components is made by means of resistance thermometers installed in them and connected to control devices. Hydrogen cooling is very efficient, because hydrogen has a high heat-transfer coefficient, high thermal conductivity, which determines the low thermal resistance of hydrogen layers in the insulation and gap grooves. Due to the low density of hydrogen, ventilation losses are reduced; as a result, generator efficiency increases [5, 6].
The absence of insulation oxidation in a hydrogen environment increases the generator reliability and increases the winding insulation service life. Another advantage of hydrogen is the fact that it does not support combustion, therefore, it is possible to forgo a fire-extinguishing device in hydrogen-cooled generators. The winding and stator core indirect cooling is carried out by a radial multi-jet circuit. In this case, the hot and cold hydrogen compartments coincide with the intakes and a gas outlet at the rotor. Hydrogen circulation by supplied by fans mounted on the machine shaft from both its ends [7, 8].

Hydrogen is cooled in gas coolers embedded in the generator housing. The cooling gas is taken from the gap with the subsequent discharge of the heated gas back into the gap. In this case, the rotor winding conductors are made of solid rectangular cross-section, and oblique ventilation ducts are milled on the side surfaces. When the generator is working (rotating the rotor), hydrogen enters the intake opening and, passing through the oblique ventilation channel to the groove bottom, goes out from the other groove (coil) side into another channel and through the exhaust port again enters the gap [9, 10].

The hydrogen pressure in the generator housing is maintained at 0.2–0.4 MPa. To cool the slip rings and brushes, to remove the brush dust from the brush-contact apparatus area, a fan is installed on the shaft between the slip rings. Generators with direct hydrogen cooling cannot operate on air cooling, because the winding is designed for forced cooling with hydrogen; if operated on air cooling they overheat and fail. Therefore, with the appearance of large hydrogen leaks from the generator, accompanied by a deep and rapid decrease in the hydrogen pressure, the generator with direct cooling should be emergency unloaded and disconnected from the network. The disconnected generator may be reconnected to the network only after the leakage has been repaired and transferred back to hydrogen, if it has been transferred to air to search for leaks [11,12].

Figure 1. The cooling scheme using ORC and an absorption refrigeration machine: 1 – pump; 2 – water line; 3 – water output; 4 – absorption machine; 5 – water-air heat exchanger; 6 – cold water input; 7 – electric generator; 8 – electric drive; 9 – atmospheric air input; 10 – atmospheric air output; 11 – low potential heat source; 12 – compressor; 13 – high potential heat source; 14 – turbine; 15 – electric generator; 16 – electric power transmission line

3. Analogues
When the generator is in operation, it is necessary to monitor the temperature of the cooling air and maintain the temperature specified in the instructions [13, 14]. This is achieved by regulating the flow of cooling water through the air coolers, depending on the water temperature and the generator load. Generator coolers must be designed so that they can provide the generator and the exciter with a nominal load with a temperature of water entering the coolers at +30 °C, and up to +33 °C if requested by customer. Coolers are calculated for a water pressure of at least 0.2 MPa. The first generators had a low-pressure hydrogen cooling system [15, 16]. The overpressure of hydrogen in such systems was 0.005 MPa.

Later, generators with a hydrogen pressure of 0.1–0.2 MPa appeared, and now they have a hydrogen pressure of up to 0.3 MPa. The use of hydrogen for cooling generators is advisable due to its...
very favorable thermophysical properties [17, 18]. The thermal conductivity of hydrogen is 6.69 times higher than the thermal conductivity of air, and the heat transfer coefficient from surface to hydrogen with a laminar flow is 1.51 times greater than that of air. The density of hydrogen is only 0.07 of the density of air; hydrogen does not cause oxidation.

The use of hydrogen as a cooling fluid made it possible to significantly improve the heat removal from the generators compared to air cooling and, as a result, to increase their power under the same electromagnetic loads. For example, the power of an air-cooled generator when working with hydrogen cooling increases from 25 to 30 MW. With hydrogen cooling, the cooling surface of the gas coolers decreases noticeably [19, 20]. As a result, it is possible to put gas coolers directly in the stator housing of a generator.

With such an arrangement of gas coolers, the pressure of the circulation pumps for supplying cooling water to the gas coolers is insufficient and therefore special, so-called lifting pumps are installed to supply cooling water. The number of these pumps per installation should be at least two: one working, one backup. Lifting pumps are connected to the pressure side of the circulation pipelines through a water filter. The backup water supply line is connected to the suction lines of the lifting pumps. Since the distribution of hot or chilled water is more difficult and costly than the distribution of electricity, Combined Cooling, Heating and Power (CCHP) automatically leads to the development of distributed generation, since the station must be closer to the consumers of heat and cooling.

4. Practical part

The process in the heat exchanger is very beneficial, since with a decrease in the temperature of a weak solution, the absorption proceeds more vigorously, and with an increase in the temperature of a strong solution, savings are achieved in the heat consumption for evaporating ammonia in the boiler generator. Since the pressure in the boiler-generator is high, and in the absorber is low, a weak solution enters the throttle valve on the way from the first to the second. The purpose and principle of operation of the condenser, the control valve, the evaporator and most of the auxiliary devices, as well as instruments in absorption machines are the same as in compression machines; therefore, the design of these parts of the machine is the same, only drainage devices replace the oil drain devices. The piston compressor in the absorption machine is absent, it is replaced with a thermochemical compressor consisting of a generator-generator, an absorber, a pump, and a throttle valve for a weak solution, interconnected by pipelines.

One of the possible areas of application of the developed technology using absorption refrigeration machines in the field of agriculture is buildings with high peak loads on the power supply system. The cost of electrical energy for air conditioning is an essential part of the building’s total electrical load. When limiting the maximum electrical power, the use of absorption chillers is a good way to minimize or smooth out peak electrical loads.

Hybrid systems are also used. In hybrid systems the basic cooling load is provided by electric chillers, and the peak one is provided by absorption refrigeration machines operating, for example, using natural gas. Absorption refrigeration machines can be used both as part of a refrigeration supply system, and as part of an integrated heat and cooling supply system. Additional energy savings can be achieved by utilizing thermal energy. The simplest chillers of this type are used in some models of domestic refrigerators operating on natural gas without electric energy.

5. Discussion

A heat pump with a compressor drive from an internal combustion engine or a gas turbine, when utilizing the heat of combustion products of the fuel and the engine cooling system, provides fuel savings already at a coefficient of more than 1.5. However, the economic feasibility of using this type of heat pump should be determined on the basis of technical and economic calculations, since specific capital costs for this type of HP are several times higher than the cost of the boiler. Use of a heat pump with a low conversion rate leads to unjustifiably high payback periods for capital investments. Absorption units of all types have a specific fuel consumption of 40–55 % if lower compared with the
boiler. Thus, fuel efficiency in the absorption unit is 1.7–2.2 times higher than in the boiler. At the same time, the cost of heat produced is 25–30% lower than in the boiler. Thus, the use of a particular type of heat pump is determined by its working conditions.

Consider an example of constructing an air conditioning system using the thermal energy from waste incineration for absorption cooling. Such a system can be implemented at any agricultural enterprise. In this case, an absorption chiller with a capacity of 600 kW was used. The air conditioning system includes three compressor chillers, each of which is equipped with four reciprocating compressors.

During the modernization, a bromide-lithium absorption refrigeration machine was installed in parallel with these chillers. The average refrigeration load of the facility is 321 kWh, the maximum 790 kWh. Since the capacity of the absorption chiller exceeds the average refrigeration load, it can be used for most of the year, estimated at about 80% of the year. With a refrigeration load of 321 kWh for absorption cooling, heat energy costs of 497 kWh are necessary with a cooling coefficient of 0.65. The system uses a cooling tower with a capacity of 1,376 kWh.

To increase the efficiency of the installation, a chilled water storage tank with a capacity of 8000 liters was installed. To transfer the heat of the flue gases to the intermediate heat carrier, a four-row heat exchanger made of steel finned tubes is used. In the cold season, when the demand for cold supply is small, the superheated flue gas is used as a heat source for the water heating system through a heat exchanger. When using the heat of the flue gases for absorption cooling, due to the lower temperature of the flue gases at the inlet of the exhaust fan, an additional saving of electric energy is provided for the rotation of the fan. So, when utilizing 497 kWh of thermal energy of flue gases, the required fan power is reduced by 8 kW.

The choice of power of the absorption refrigeration machine was determined by the ratio of the average refrigeration load to the maximum. If peak load is observed only for a short period, absorption cooling is more economical if it covers the average cooling load. With an average refrigeration load of 321 kWh and an average refrigeration coefficient of 2.9 for compressor refrigeration machines, 110 kW of electric power is required to remove the refrigeration load. When using thermal energy from waste incineration for absorption cooling, this electrical energy is not used. Additional savings, as mentioned above, are achieved by reducing the temperature of flue gases, at which the electric load of the exhaust fan is reduced by 8 kW.

However, with absorption cooling, additional power supply of 8.2 kW is also required directly to ensure the operation of the absorption refrigeration machine, 2 kW for the cooling tower fan, 7.8 kW for the operation of circulation pumps. Thus, a net reduction in electrical load is 101 kW. The waste incineration line operates seven days a week in three shifts, and its operating time per year is 8,064 hours with a load factor of 0.868. Thus, the annual economic effect of introducing the utilization of flue gas heat on absorption cooling will be more than 10 million roubles. The payback period without taking into account the discount factor will be less than five years.

6. Conclusion
As a result of the calculations, the possibility of using absorption refrigeration machines in agriculture is justified. The operation of such machines is associated primarily with cooling products of enterprises. However, as shown in the article, the use of an absorption machine may be associated with cooling the turbine generator.

According to the proposed method, the turbine works in conjunction with the organic Rankine cycle. Electricity generated in the ORC is used to power the pumps. The payback period of the project when it is implemented at agricultural enterprises will be from 3.4 to 5.0 years, depending on the productivity of the enterprise.

In addition, the economic effect of the installation was calculated. It will be approximately 10 million roubles. In addition, during the calculations, the dependences of the consumed and generated electricity in various operating modes of the absorption cooling unit and the Rankine organic cycle were obtained.
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