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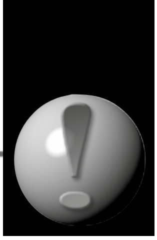

Analysis of the Issue of Recovery of Low-Potential Energy at Small-Scale Energy Facilities

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ABSTRACT

Studying the issues of recovery of low-potential energy at small-scale energy facilities allowed to show the promising character of the organic Rankine cycle (ORC) technology as a technology for recovery or conversion of low-potential energy.

The most promising developments in the field of the use and recovery of waste heat are described regarding application of ORC, which is widely used in geothermal sources, hot water boilers, gas turbine plants. Due to the constantly growing diversity of working fluids, ORC can be used within a wide temperature range from 100°C to over 350°C. Also, developments are underway in the design of ORC generators to increase reliability of its individual system units, such as turbines and expanders. Based on the above factors, it can be concluded that with a deeper study of the problems of adopting ORC technologies, they can become a very promising direction in development of heat power engineering.

It has been determined that the main factor hindering the widespread adoption of the ORC technology is associated with high cost of heat exchange equipment due to increased heat exchange surfaces. It is shown that design of mini power plants and energy centres based on the use of low-potential energy requires improvement of mathematical modelling methods to reliably determine operating modes and characteristics of each of the units. Methods for modelling evaporation and condensation systems, including turbines and expanders using organic low-boiling working fluids, should be considered among the methods that are highly sought after. The methods for selecting a working fluid for ORC devices also have a significant impact on characteristics of the installation determining the range of cycle operating temperatures and pressures. The solution of the above problems can lead to a reduction in the cost of heat exchange equipment, and, consequently, to a decrease in costs for design of ORC generators.

Keywords: *low-potential energy resources, organic Rankine cycle, mini electric plant, energy centres, mathematical modelling.*

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INTRODUCTION

The need to consider current technological conditions regarding the recovery of low-potential energy at the small-scale energy facilities is determined by the demand for a more economical use of energy resources due to the passed peak of hydrocarbon extraction. In Russia it is due also to implementation of the national Energy Strategy until 2035[1]. At the present stage of development of industrial production, it is the adoption of energy-saving technologies that allows to increase efficiency of the use of fuel and energy resources, while the latter is among the main conditions for reducing the fuel component in the cost of production, and, accordingly, for increasing profitability of enterprises. Almost all the enterprises of stationary power engineering in transport and other industries, as well as in agriculture, have «excess» heat of the working fluid in cooling systems that ensure stable and continuous operation of production cycles [1−4].

The last decade has been marked by the widespread of installations operating according to the organic Rankine cycle (ORC) with the use of turbine generators both for producing electricity and operating according to the cogeneration [5]. The main equipment of the generator, as a rule, includes heat exchangers, piping, primary and secondary coolant pumps, a turbine, an electric generator, an automation unit with power equipment. Recently, modular power blocks have become widespread due to the ease of installation and lower transportation costs. In practice, such turbine generators have a fairly wide range of electrical power (50−1000 kW).

The modern scientific literature describes results of analytical reviewing of thermal schemes of power recovery plants, working fluids, methods of thermodynamic evaluation of the efficiency of heat conversion processes [1−13]. In Russia, the first systemic studies were carried out by M. I. Dunaevsky, and then M. M. Grishunin, A. P. Sevastyanov, L. I. Seleznev, E. D. Fedorovich were engaged in development of technological schemes and cycles [14; 15].

[1] Energy Strategy of the Russian Federation for the period until 2035 [in Russian]. Resolution of the Government of the Russian Federation dated June 9, 2020, No. 1523-r. [Electronic resource]: https://minenergo.gov.ru/node/1026. Last accessed 09.01.2021.

The *objective* of the article is to consider the current state of the issue on recovery of low-potential energy resources to improve the energy efficiency of small-scale energy facilities and to identify the main problems facing such energy centres.

MAIN RESULTS

Over the past 10 years, much attention has been paid globally to design and development of low-power energy-efficient electrical installations based on closed steam turbine cycles in low-boiling working fluids (LBWF). An energy source of heat is low-potential if its temperature does not exceed 230–300°C (500–570 K). Fundamentally, LBWF determine the type of thermodynamic cycle, the composition of the equipment and technical and economic indicators of power plants. The broadest group includes pure (s opposed to blends) LBWF: hydrocarbons (butane, propane, pentane), freons (R11, R12, R114, R123, R245fa), ammonia, toluene, diphenyl, silicone oil, etc. They are used in power plants, implementing ORC, the essence of the application of which is recovery of secondary energy resources (SER), having a temperature of 80−350°C (waste gases, cooling water and other SER of technological processes) [16].

ORC is mainly used in:

- thermal power plants;
- geothermal power plants;
- landfills for disposal of biological waste;
- industrial enterprises that have waste heat in their production cycle;
- gas turbines, internal combustion engines, etc.

The range of application of working fluids depends on the criteria applied to them: energy properties, low ozone depletion potential, operational safety.

ORC-based power plants have the following advantages:

- lower capital costs for a turbine in comparison with a steam-water analogue;
- there is no need for a water treatment system;
- simple start-stop procedure;
- long service life of turbine equipment (up to 30 years [1]).

Considering these advantages, the use of closed steam turbine cycles in low-boiling working fluids is very promising at the facilities that dispose waste heat.

Use of ORC at Geothermal Sources

A rather interesting example of the use of ORC is its use at geothermal sources. Warm geothermal waters act as a source of heat for ORC at the geothermal power plant. Geothermal waters are pumped from the bowels of the earth to the evaporator, where they give off heat to the LBWF. The world's first geothermal power plant (GeoTPP) using LBWF, or, as it is also called, the binary GeoTPP, was created in the USSR in Kamchatka (Paratunskaya GeoTPP) in 1967. Geothermal waters with a temperature of 81°C served as the heat source. The working agent was R12 freon. The plant generated power of 680 kW. At the same time, practical implementation of binary GeoTPP (USA, Mexico, Argentina, Iceland, Italy, Austria, Germany, Portugal, Israel, Thailand, China, Taiwan, New Zealand, Philippines, Japan) is becoming more active all over the world, with the defining trend to create small, fully automated, modular installations that do not require constant maintenance. ORMAT (Israel) is the leader in their production (up to 1000 installed power modules using pentane with a capacity of 40 kW to 3,5 MW) [9].

Application of ORC with a Hot Water Boiler

The adoption of the ORC technology at the hot-water boiler house makes it possible to create cogeneration: simultaneous generation of heat and electricity. Depending on the consumer, the mini TPP can switch between generation modes both to generate electricity either to supply heat by changing the flow rate of the coolant towards the evaporator of ORC generator or the heating network [12].

Implementation of ORC Technologies in the Circuit of Combined-Cycle Gas Turbine Plants

When using ORC with gas turbine units (GTU) and depending on temperature and volume of exhaust gases, there are two methods of designing ORC superstructure [13]:

- ORC superstructure for combined-cycle gas turbine plant by connecting ORC to heat extraction of the steam turbine;
- ORC superstructure for GTU via waste heat recovery boiler.

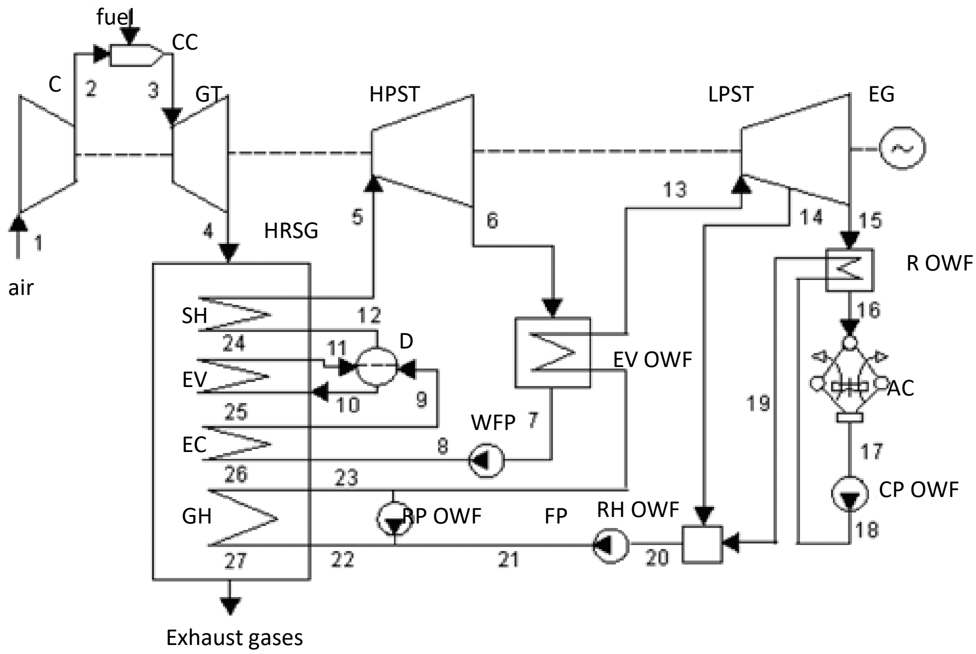
These methods make it possible to generate additional energy from exhaust gases.

Several scientific institutions in Russia have got significant research experience in the study of ORC processes, namely, of working fluids for steam turbine cycles, building thermal circuits and calculating its constituent elements (turbines and heat exchange equipment of various types) [3].

The study [16] performed the analysis and substantiation of the solution of the problem of energy saving on the basis of implementation of closed steam turbine cycles in low-boiling working fluids for industrial facilities with the use of SER. A study was carried out on selection of low-boiling working fluids used in ORC circuits. Calculations have been carried out to assess possible obtained electrical power during the implementation of LBWF turbines using waste gases of a water boiler unit with a capacity of 100 Gcal/h. It is shown that with the maximum use of heat of exhaust gases, electric power of the LBWF installation can reach ~2900 kW. To determine the most effective way of recovery of exhaust gases, a search was made for a rational thermal scheme, considering the characteristics of the existing technological cycle. In [9], based on available operating characteristics maps of the boiler unit, computational studies were carried out to determine possible electric power depending on the operating mode. Calculations have shown that the use of heat of exhaust gases without additional combustion of fuel limits the maximum temperatures of LBWF and does not allow reaching the maximum power of the power plant of ORC circuit through a small heat drop generated by the turbine. A greater amount of heat can be achieved only by increasing consumption of a low-boiling working fluid, which is not always optimal. An increase in flow rate of the working fluid entails an increase in the mass and size characteristics of heat exchange, auxiliary and turbine equipment.

At the present stage of development of closed-cycle steam turbines with low-boiling working medium, it is advisable to choose an option that will cover own needs of a heat-generating installation for electric energy at the level of 5–10 % without additional fuel combustion.

When determining feasibility of adopting the ORC cycle, it is necessary to consider that each individual case requires assessment of the



Pic. 1. Cycle diagram of combined-cycle gas turbine plant [7]: C – compressor, CC – combustion chamber, GT – gas turbine, HRSG – heat recovery steam generator, ST – steam turbine, HPST – high pressure steam turbine, LPST – low pressure steam turbine, SH – superheater, EV – evaporator, D – drum, EC – economizer, GH OWF – gas heater for organic working fluid, EV OWF – evaporator of organic working fluid, WFP – water feed pump, R OWF – recuperator of organic working fluid, AC – air condenser, CP OWF – condensate pump for organic working fluid, EG – electric generator, RP OWF – recirculation pump for organic working fluid, FP OWF – feed pump for organic working fluid, RH OWF – regenerative heater for organic working fluid.

amount and parameters of low-grade heat, as well as a complete feasibility study.

The development and implementation of installations are carried out by well-known companies from the USA, Japan, Belgium, Israel, Italy, Russia and other countries [12; 13; 17; 18].

Currently, the developed installations are intended to use low-potential SER with a temperature of 100–120°C, R142b as a working coolant and to have the efficiency of 0,08–0,10. There is a need to determine the coolant that provides optimal efficiency of the Rankine cycle for each temperature of SER sources. Therefore, for a certain specific source of SER, a thermal scheme of the installation is developed with its proper characteristic parameters and a working coolant. With a decrease in the temperature of the SER source, the cost and complexity of the equipment increases (up to 1500–2000 $1 per kW of power) [10].

SER sources with a temperature of 150–170°C need recovery by power plants with a isobutane (C_4H_{10}) or a mixture (isobutane/isopentane) working coolants. Thermal circuits with *n*-pentane and hexane are being developed for recovery of SER with higher temperatures (200–250°C).

Organic heat transfer media have not been studied enough for recovery of SER with temperatures above 300–350°C. Therefore, thermal schemes of installations with water vapour and carbon dioxide (CO_2) were developed.

From the above description of the ways of adoption of ORC installations, it can be concluded that this branch of electrical and heat engineering is sufficiently developed to create industrial designs. Therefore, ORC plants are increasingly being used in energy centres. The main world leaders who have mastered this industry are now ORMAT, Electratherm, Turboden, which have a wide range of capacities, structural solutions, as well as solutions regarding modular blocks that simplify installation and operation of ORC units.

However, despite apparent maturity of approaches to the problem of designing ORC generators, high capital costs due to suboptimal weight and size characteristics of the heat exchange equipment remain limiting factors for widespread introduction of these

Pic. 2. Semi-hermetic twin-screw HSE.85 expander [19].

installations. This negative factor might be overcome by compilation of such mathematical models that most reliably describe the processes in the systems of evaporation, condensation, and gear boxes.

The work [7] inspires interest from the point of view of analysis since it considers a three-stage steam gas plant and proposes a scheme for deep recovery of exhaust gas heat through the introduction of the ORC technology. The scheme is implemented as follows: the topping cycle is expressed by the Brighton cycle, the middle one is the Rankine cycle using water vapour, and the bottoming one is ORC. The schematic diagram of combined-cycle gas turbine plant is shown in Pic. 1 [7].

In the presented combined-cycle gas turbine plant, temperature in front of the high-pressure steam turbine is about 1527°C (1800 K), temperature of exhaust gases of the topping cycle is about 477°C (750 K), the medium steam-water cycle operates in the temperature range of 527°C (800 K) in front of the medium-pressure turbine and 77°C (350 K) in the condenser. The condensation temperature in ORC can be below 0°C (273 K) due to the use of air condensers in the northern regions of the country, where for about 8 months a year the ambient temperature is below 0°C.

The medium steam-water cycle can be replaced by the organic Rankine cycle with a lower condensation temperature of the working fluid than the water has, thereby lowering the condensation temperature limit for a deeper heat recovery in the middle cycle and an increase in efficiency throughout the plant.

The mathematical model proposed in [7], despite a very versatile approach to the method of deep recovery of low-grade heat, is expressed by a mathematical model of the first level, that is, linear equations, with a large number of assumptions and approximations, which may affect reliability of the processes described therein.

Other Applications of OCR Technology

The use of ORC technology is not limited only to stationary power devices. One of the possible options for modernisation of existing piston engines used in sea and railway transport to increase their efficiency is the use of ORC units integrated into the engine operation. The ORC system can recycle either high-grade (exhaust gases) or low-grade (cooling water) heat, or a combination of both, providing an increase in fuel efficiency of up to 12 % [19]. The engine radiator can be replaced, which reduces the capital cost of ORC generator by 30 % of its total cost, with a payback period of less than five years for diesel engines. So, ElectraTherm company in 2020 presented a commercial model of a semi-hermetic expander operating on 1,1,1,3,3-pentafluoropropane, shown in Pic. 2.

The expanders are easier to operate than freon turbines: they work more efficiently at low rotation speeds, they do not need an oil pump, there are no stuffing box seals, it is possible to work under wet running conditions (when the working fluid partially enters the expander in a liquid state) [20].

However, a factor hindering modernisation is weight and size characteristics of non-technological heat exchangers, the calculations of which are carried out, often according to existing simplified engineering techniques with a high margin for the heat exchange surface due to complexity of describing real processes, which leads to an increase in weight and size characteristics of heat exchangers. By constructing various mathematical models, the [21] considered the process of condensation of the working fluid.

It was proposed to pass working fluid through a steel pipeline embedded in the ground to condensate it. The mathematical modelling used tools of engineering calculation methods and ANSYS CFX software package. Using various modelling approaches, when considering this issue, it was proposed to determine the optimal length and diameter of the pipeline. The study found that the divergence of the final length of the pipeline with the same degree of steam dryness (0,00) was more than 30 m. According to the engineering method of calculation, the length was about 107 m, while the length obtained in ANSYS CFX software package was 70 m. The study did not consider the thermal contact of the pipe with the ground, the polytropic nature of the real process, the change in thermophysical properties of the coolant due to hydraulic losses.

As it is known, it is also possible to reduce dimensions of the heat exchanger by forcing heat transfer. The existing methods of intensifying heat transfer are carried out by increasing the turbulence of the flow by means of ribbing, creating hemispherical protrusions along the length of the channel wall, making screw inserts and with other methods. These solutions have found wide application in design [4; 6].

A less studied method for increasing thermal conductivity of the working fluid is associated with the addition of insignificant impurities (less than a fraction of a percent) of nanosuspensions in the form of metal oxides, which increases thermal conductivity up to 60 % [11]. This solution, together with the use of an expander, due to its great simplicity in operation, can contribute to an increase in compactness of the ORC installation.

Despite the fact that the idea of heat recovery at the expense of ORC was proposed a long time ago, adoption of this technology requires solving problems of design optimisation and calculation of all units included in the scheme for recovery of low-potential energy [1–4; 6–8; 16–20].

Research continues to improve the methods for calculating the units of evaporation and condensation of the working fluid of ORC, as well as turbines and expanders [1–4; 6–8; 16–20].

CONCLUSIONS

The analysis performed allows us to conclude that the main factor hindering widespread adoption of ORC technology is high cost of heat exchange equipment due to increased heat exchange surfaces. In this regard, design of such mini electric plants and power centres requires improvement of mathematical modelling methods to reliably determine operating modes and characteristics of each of the units. These popular methods include the methodology for calculating evaporative and condensing systems, as well as turbines and expanders using organic low-boiling working fluids. The solution of the above problems can lead to a reduction in the cost of heat exchange equipment, and, consequently, to a decrease in the costs of designing ORC generators.

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