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Investigation of a binary power plant using different single-component working fluids☆

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ABSTRACT

The tendencies of the development of geothermal energy technologies on the base of utilizing geothermal fluid of different temperature are studied. It is shown that in recent years there are an increasing number of countries where the growth of installed capacity of geothermal power plants is mainly due to the construction of power units with a binary cycle. It allows to expand the resource base of geothermal energy through the development of low-temperature geothermal sources, the total capacity of which exceeds the one of high-temperature resources. It is noted that the low-temperature geothermal sources are widely available and in fact can be utilized almost anywhere in the world. The analysis of the scale and geography of the application binary energy technologies for the development of geothermal resources are shown. The features of the use of organic working fluids in binary power plants are described. The basic principles of the optimal working fluid selection for binary plant are explained. The results of numerical modeling of the working fluid selection on the performance of binary power plants are presented. It is shown, that use of the hydrogen-oxygen steam generator in combined power plants can increase the effectiveness of geothermal utilization.

Introduction

The modern geothermal energetics is characterized by increasing interest to the binary power technologies, which allow dilating its resource base essentially at the expense of involving low-temperature sources in electrogeneration. In a binary power station the process of heat transfer from geothermal fluid to other low-boiling fluid which is an organic working fluid of the second closed loop is provided.

The geothermics advancement rested initially on the development of geothermal high-temperature resources, mainly in the form of over-heated steam. Later on, geothermal moist steam or water-steam mixture became the basic primary source for Geothermal Power Plant (GPP). Nowadays the development of geothermal power in many countries is carried out at the cost of the low-temperature fluid's heat utilization, as well as waste geothermal brine of operating GPPs in terms of the binary power plants' usage.

Use of low-boiling organic working fluids in the second circuit of binary power station allows utilizing fluid's heat at temperatures from 80 °C to 250 °C. The GPPs, built in Russia (overall 12 power units with total capacity of more than 80 MW) use geothermal fluid in the form of water-steam

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Nomenclature

G	flow rate, kg/s, m^3/h
GPP	geothermal power plant
N	capacity, power, MW
P	pressure, MPa
TLV	threshold limit value
U.S.	United States
WGC	world geothermal congress
Greek letters	
Δ	difference of values
$\sum$	sum, total
η	efficiency, %
Superscripts and subscripts	
au	auxiliaries
el	electrical
ev	at the evaporator exit
exp	expansion
geo	geothermal fluid
n	net
out	out, in condenser
wf	working fluid
H_2	hydrogen
O_2	oxygen
RC-318	octafluorocyclobutane
R-134a	tetrafluoroethane
R-152a	1,1-difluoroethane

mixture by pumping liquid phase (geothermal brine) back into the seam. Appliance of binary power stations, capable of utilizing this waste fluid's heat, should provide increase in capacity of domestic GPPs by 20–25% without circle flood.

Features of use of low-boiling organic working fluids in binary power stations

The first geothermal power plant in the world with a binary cycle was built at Russian Kamchatka in 1967 (Paratunskaya GPP) [1]. Freon was used as organic working fluid in the second circuit. It was heated up by geothermal water at temperature close to 90 °C and was used in the form of steam in a turbogenerator for electric power development.

The total installed capacity of geothermal stations with binary cycle in 25 countries is 1790 MW, including 873 MW in U.S., 265 MW in New Zealand and 219 MW in Philippines, according to WGC-2015 [2]. The pilot geothermal power plant with binary cycle having a capacity of 2.5 MW was developed and built in Russia at Paratunskaya GPP for heat utilizing of the waste geothermal fluid of the operating GPP [3,4].

Today binary power plants with geothermal fluid of different temperature levels are maintained. Fig. 1 shows information on the number of binary power plants, utilizing geothermal fluid of different potential. The overwhelming majority of operating binary power plants utilizes geothermal fluid heat at temperature range within 100 °C–200 °C.

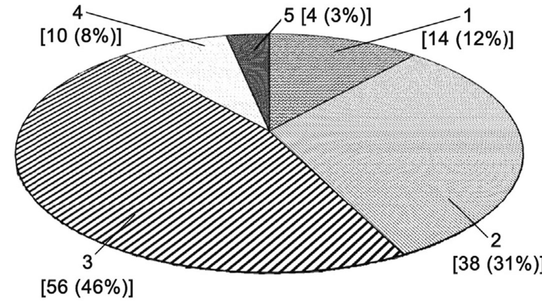

Fig. 1 – Information on the number of binary power plants, utilizing geothermal fluid of different potential: 1 – less than 100 °C; 2 – 100–150 °C; 3 – 150–200 °C; 4 – 200–250 °C; 5 – more than 250 °C.

Selection of organic working fluid is one of the most complex and responsible problem during the development and construction of binary power plants. The physicochemical properties of organic working fluid alongside with geothermal fluid's features (which depend on GPP location) make essential impact on the optimum thermal schema, design and technical characteristics of the binary power station's equipment.

While selecting low-boiling organic working fluid, it is necessary to assure that it is stable, nonflammable, nonexplosive, non-toxic, inert to applied constructional materials and soft for the environment. The effective selection of the organic working fluid is hindered by the fact that one requirement often contradicts another. Almost all of the binary power plants actually utilize hydrocarbons today (Fig. 2) [5].

Having different good thermodynamic and thermal features, rather cheap hydrocarbons (pentane, isobutane, isopentane, etc.) are fire and explosion dangerous and can be used in outdoor powerhouse only that is unacceptable for Russia and for regions with negative winter temperatures.

Comparative characteristics of binary power plants, utilizing different organic working fluids

In justifying the selection of low-boiled organic working fluid of binary power plants designed for operation in Kamchatka and in other regions of Russia with negative winter temperatures, the complex of settlement researches covering the

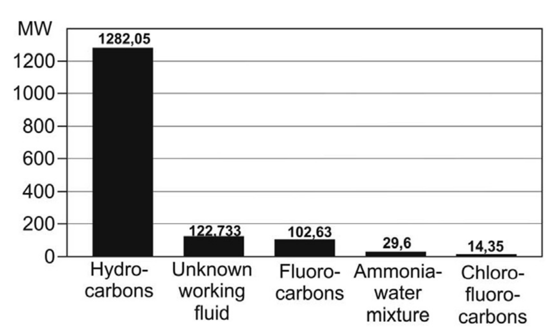

Fig. 2 – Information about the total installed capacity of binary power plants and their working fluids.

effect of different organic working fluids on main technical characteristics of binary power plants was carried out. Table 1 presents the investigated low-boiled organic fluids. It was necessary to estimate possibilities and features of different fluorocarbons as organic working fluids for domestic binary power plants within the framework of these studies. The relative calculations for traditional thermal schema of the binary power plant with vaporizer-steam superheater, turbine, condenser and feed pump were made.

The investigated organic working fluids have rather close values of critical temperatures and refer to different evaluation classes. Thus, R-134a and RC-318 refer to A1 class that is nonflammable and nonexplosive, R-152a refers to A2 class (nonexplosive but flammable), and propane refers to A3 class (explosive and flammable). All fluids have the same threshold limit value (TLV), which is equal to 1000mg/m3.

The initial geothermal fluid temperature equal to 120 °C and quenching water equal to 8 °C were considered in calculations. Besides, power plant capacity was set to gross 2630 kW (that corresponds to 2500 net kW).

Fig. 3 shows the results of settlement researches of the selected organic working fluid effect on geothermal fluid (or geothermal brine for Russian GPPs, where geothermal fluid is used as water-steam mixture) and organic working fluid of binary power plant flow rates. Maximum flow rate of geothermal fluid for examined power plant corresponds to RC-318 and R-152a usage, while minimum flow rate corresponds to R-134a and propane. Thus geothermal fluid (liquid phase) flow rate equal to 117,9 kg/s is required to maintain given power of the binary power plant utilizing R-134a. In this case R-134a flow rate will be 144,8 kg/s that is quite a reduction compared to flow rate of RC-318, but is much greater than for R-152a and propane flow rates.

It ought to be noted that R-134a practically does not require geothermal fluid's flow rate increase, as compared to organic fluids like propane used in binary power plants extensively.

Fig. 4 shows how calculated values of organic working fluid selection effects such calculation characteristics of vapor turbine as the steam pressure at the turbine inlet and the volume flow rate at the turbine outlet. Utilization of R-134a almost four times declines the pressure at the turbine inlet as compared with propane and affects turbine's construction positively including reduction of steel needed. The important fact herewith is insignificant change in the volume flow rate at the turbine outlet while changing from R-134a to propane.

Generally, rather high values of auxiliaries are typical for binary power plants and they affect the net efficiency negatively as a consequence. Therefore it is important to evaluate the effect of organic working fluid selected on this certain characteristic of binary power plant. Fig. 5 shows calculated values of auxiliaries (per cent their share in net efficiency) of the binary power plant with different organic working fluids. Utilization of R-134a instead of propane allows almost three times decline of power expenditures to cover auxiliaries' value. Net efficiency's calculated values of binary power plant with different organic working fluids differ in the range from 8,05% to 8,93%.

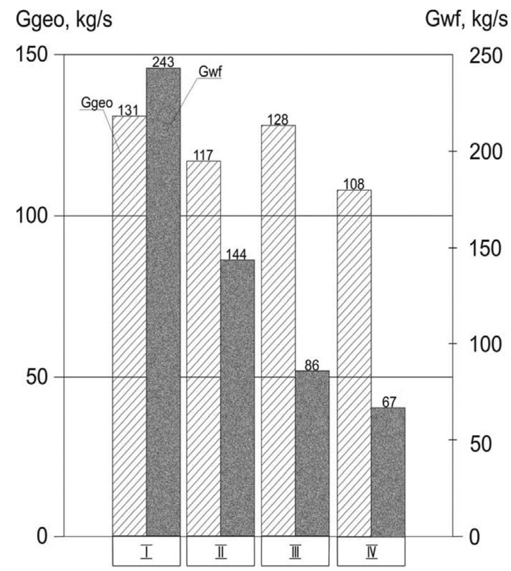

Fig. 3 – The calculated values of geothermal fluid (G_{geo}) and working fluid (G_{wf}) flow rate for a 2630 kW-binary power plant with different organic working fluids: I – RC-318; II – R-134a; III – R-152a; IV – propane.

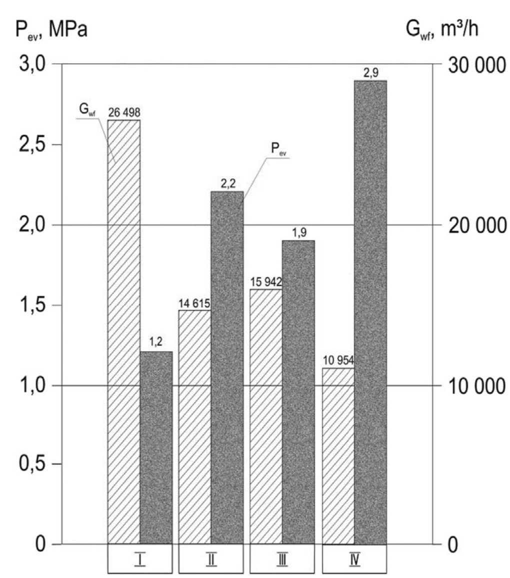

Fig. 4 – The calculated values of the pressure at the turbine inlet (P_{ev}) and the volume flow rate (G_{wf}) at the turbine outlet for a binary power plant with different organic working fluids: I – RC-318; II – R-134a; III – R-152a; IV – propane.

Table 1 – The list and the properties of the investigated working organic fluids.

Characteristic	Working fluid			
	RC-318	R-134a	R-152a	Propane
Chemical formula	C_4F_8	$C_2H_2F_4$	$C_2H_4F_2$	C_3H_8
Molar mass, kg/kmol	200,03	102,03	66,05	44,1
Critical temperature, °C	115,2	101,1	113,2	96,7
Critical pressure, MPa	2,78	4059	4,52	4,25

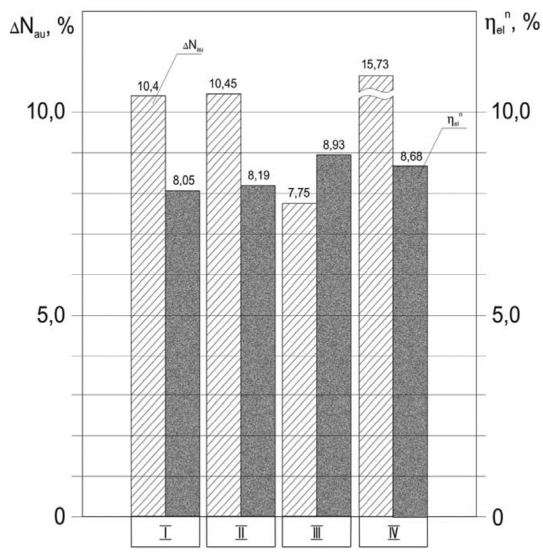

Fig. 5 – The calculated values of auxiliaries (ΔN_{CH}) and a net electrical efficiency ($\eta_{el}{}^{n}$) for a binary power plant with different organic working fluids: I – RC-318; II – R-134a; III – R-152a; IV – propane.

The use of steam overheating in combined geothermal power plants with binary cycle

The main trend in geothermal energetics development nowadays is development of projects concerning increase of installed capacity of operating domestic and foreign geothermal stations with binary cycles by utilizing waste geothermal brine on the basis of application of power plants with combined and binary cycles without drilling new mines. One promising way to improve combined geothermal power plants with binary cycle utilizing water-steam mixture is geothermal steam superheating before the turbine. It enables the reduction of wetness degree in turbine flow tube and leads to increase in efficiency as well as to reduction of nozzle vanes and turbine rotor blades' impingement corrosion. General efficiency of a thermal cycle could be also increased by rising steam temperature by means of hydrogen-oxygen steam generator before turbine [6].

The increase of installed capacity of Mutnovskaya GPP by means of the waste geothermal brine heat in combined power plant with binary cycle is one of advanced domestic geothermal projects. The main point of the project is utilization of waste geothermal brine heat from first stage of Mutnovskaya GPP in direct and vapor cycle turbines (i.e. implementing combined cycle). Secondary steam obtained at dilating of waste geothermal brine is utilized in steam turbine, and residuary geothermal brine goes to vapor turbine plants. In this case the pilot project of binary power station at Pauzhetskaya GPP [7] with organic working fluid R-134a is going to be used as binary power plant prototype. Project implementation will allow increasing the efficiency of extractive geothermal fluids utilization and obtaining additional capacity at Mutnovskaya GPP.

Power system of geothermal power plant with combined cycle consists of two circuits. The organic working fluid of the first circuit is geothermal fluid and steam and geothermal brine derived from it in expander. The organic working fluid is utilized in the second circuit. According to the block diagram (Fig. 6), geothermal fluid enters the expander from geothermal field at operating Mutnovskaya GPP-1. Secondary underpressure steam leaves expander for separator, and then goes to steam turbine, where it performs an operation; it goes further to condenser and then it is pumped into reinjection wells.

Geothermal brine goes from expander and separator to heat exchange devices (steam generator, evaporator and economizer), where it gives up its heat to organic working fluid, and then it's pumped through pipeline into reinjection wells. The steam of working fluid leaves steam generator and goes to vapor turbine, where it diverges, and then it condenses in condenser; then condensate is pumped up by feed pump into evaporator.

In order to increase the efficiency of combined geothermal power plant with binary cycle, the built-in hydrogen-oxygen steam generator was suggested to be added into flow sheet (See Fig. 6). Additional electrical output of geothermal power plant with combined cycle could be provided by use of hydrogen-oxygen steam generator due to steam flow increase as well as to its additional overheating during direct contact with steam from steam generator. While carrying out calculated optimization study the increase of power plant capacity connected with steam overheating increase was taken into

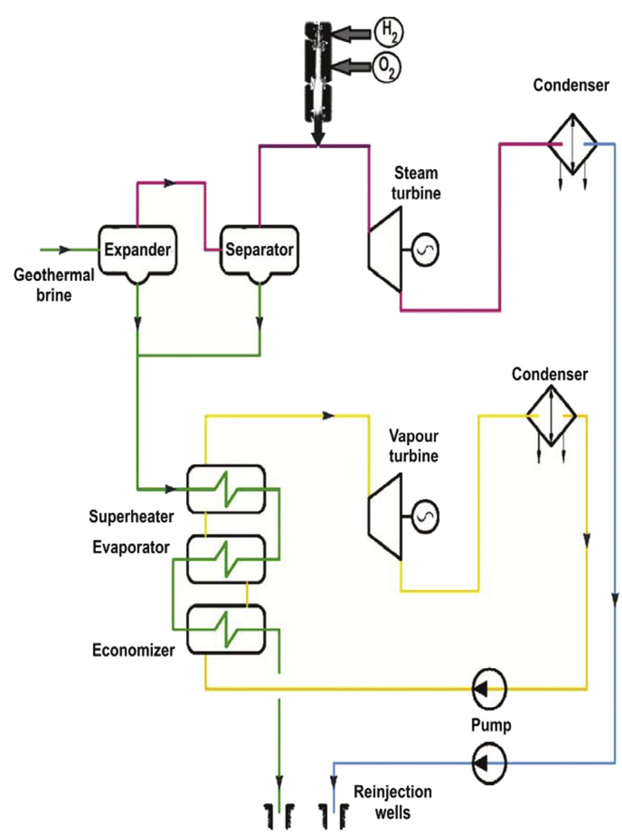

Fig. 6 – Principal balance of plant diagram of a combined (steam-and-binary) power plant with hydrogen–oxygen steam generator.

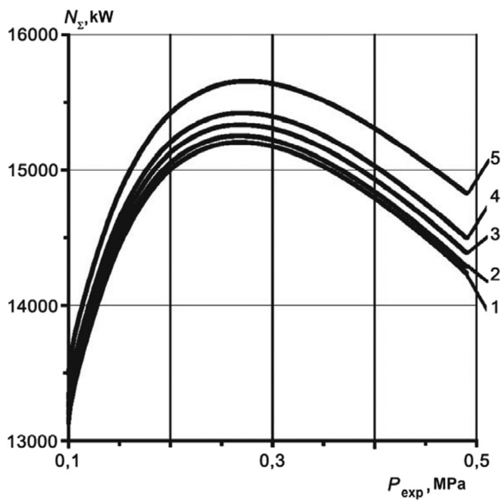

Fig. 7 – Investigation on the influence of pressure expansion (P_{exp}) values of geothermal fluid on combined power plant (with binary cycle) output at a condensing pressure P_{out} = 0,007 MPa, and various thermal power of a hydrogen-oxygen steam generator: 1 – QH_2O_2 = 0 kW; 2 – QH_2O_2 = 200 kW; 3 – QH_2O_2 = 600 kW; 4 – QH_2O_2 = 1000 kW; 5 – QH_2O_2 = 2000 kW.

consideration. Such approach allows estimating efficiency usage of geothermal steam "from below", since from the point of view of thermodynamics, it is more effective to use hydrogen fuel on steam flow increasing and its additional overheating.

Fig. 7 shows the calculated influence of the capacity of combined geothermal power plant with binary cycle on expansion pressure at different values of thermal power hydrogen-oxygen steam generator. It was specified that in optimum range of geothermal brine expansion pressure values from 2.5 to 3.0 MPa, the ultimate capacity gain of combined geothermal power plant with binary cycle coincides the thermal power of hydrogen-oxygen steam generator of 2000 kW. The use of steam overheating system pressure at the turbine inlet by means of hydrogen-oxygen steam generator could be the promising way to increase maintainability and running efficiency of geothermal power plants with binary cycle.

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