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GEOTHERMAL ENERGY

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1. General concepts and characteristics

Geothermal energy is the energy of the Earth's subsoil, which is found in solid rocks and groundwater of the Earth. The temperature of the Earth's crust increases by 2.5…3 °C every 100 m. So, at a depth of 20 km the temperature is about 500 °C, at a depth of 50 km it is about 700…800 °C. In certain places, especially at the edges of continental tectonic plates, as well as in so-called "hot spots", the temperature gradient is almost 10 times higher, and then at a depth of 500...1000 meters the rock temperature reaches 300 °C.

Geothermal reserves are divided into hydrothermal and petrothermal. Hydrothermal reserves are water, vapors or vapor-water mixtures which project through the cracks of rocks and have a temperature of 200…300 °C, water streams or aquifers of 80…95 °C. The method of using geothermal resources depends on the temperature of the coolant. At temperatures above 120…150 °C, it is advisable to use the electricity in the production. At lower temperatures the geothermal reserves are used for heating systems, air conditioning, water heating of urban and industrial hot water supply systems, for heating of greenhouses, fisheries, for recreational purposes.

Geothermal energy sources are divided by the physical state of the heat carrier and by temperature into the following groups:

- soils and rocks up to a depth of 2500 m, from which heat for heating using heat pumps is obtained by means of special heat probes;
- groundwater directly used as a heat source for heat pumps;
- water vapor obtained by wells supplying water, which is used in geothermal power plants for electricity production;
- salt deposits, the energy of which is derived by brine or inert liquids, such as isobutane;
- hot rocks from which the energy is produced by high pressure water circulating through a system of artificial or natural cracks in rock

complexes at considerable depth. This energy is used in geothermal power plants to produce electricity as well as for heating.

The use of geothermal energy can make a significant contribution to solving the following urgent problems:

- ensuring sustainable heat and power supply to the population in the areas of our planet where centralized energy supply is absent or too expensive (for example, in Russia in Kamchatka, in the regions of the Far North, etc.);
- ensuring a guaranteed minimum of energy supply to the population in the areas of unstable centralized energy supply due to electricity shortages in the power systems, preventing damage from emergency and restrictive shutdowns, etc.;
- reduction of harmful emissions from power plants in selected regions with complex environmental conditions.

2. World geothermal energy potential and prospects for its use

A group of experts from the International Geothermal Association, which has evaluated the low- and high-temperature geothermal energy reserves for each continent, according to the potential of different types of geothermal Earth sources, obtained the data listed in Table 1.

Table 1

The Earth's geothermal energy reserves

The name of the continent	The type of geothermal source		
	high temperature used for electricity production, TJ/year		low temperature used in the form of heat, TJ/year (lower limit)
	traditional technologies	traditional and binary technologies	
Europe	1830	3700	>370
Asia	2970	5900	>320
Africa	1220	2400	>240
North America	1330	2700	>120
Latin America	2800	5600	>240
Oceania	1050	2100	>110
World potential	11200	22400	>1400

As can be seen from the table 1, the potential of geothermal energy sources is enormous. However, it is used to a small extent: the capacity of geothermal thermal power plants (GeoTPP) in the world in the early 1990s was about 5000 MW, and in the early 2000s – about 6000 MW, substantially inferior by this indicator to most power plants operating on other renewable energy sources. And electricity production at GeoTTP was negligible during this period.

It is known that geothermal resources have been explored in 80 countries and are actively used in 58 of them. The most powerful producer of geothermal power is the USA, where geothermal energy, as one of alternative forms of energy, has special government support. In the United States in 2005, about 16 billion kWh of electricity was generated at GeoTTP in major industrial areas such as the Great Geysers Zone, located 100 km north of San Francisco (1360 MW of installed capacity), the northern Salt Sea in the central California (570 MW of installed capacity), Nevada (235 MW of installed capacity), and more.

In the table 2. the comparative characteristics of the use of geothermal resources in different countries for the years 2000–2019 are given.

Table 2

The direct use of geothermal resources in different countries of the world

Country	Capacity, MW		Annual production				Capacity factor	
			TJ/year		GWh/year		(the share of maximum capacity per year)	
	2000	2019	2000	2019	2000	2019	2000	2019
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Algeria	100,0	152,3	1586	2417	441	671,4	0,50	0,50
Argentina	25,7	149,9	449	609,1	125	169,2	0,55	0,13
Australia	10,4	109,5	294	2968	82	824,5	0,90	0,86
Austria	255,3	352,0	1609	8027,64	447	2229,9	0,20	0,20
Belgium	3,9	63,9	107	431,2	30	119,8	0,87	0,21
Bulgaria	107,2	109,6	1637	1671,5	455	464,3	0,48	0,48
The United Kingdom	2,9	10,2	21	45,6	6	12,7	0,23	0,14
Venezuela	0,7	0,7	14	14	4	3,9	0,63	0,63

Table 2 (continuance)

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Greece	57,1	74,8	385	567,2	107	157,6	0,24	0,24
Georgia	250,0	250,0	6307	6307	1752	1752,1	0,80	0,80
Denmark	7,4	821,2	75	4360	21	1211,2	0,32	0,17
Israel	63,3	82,4	1713	2193	476	609,2	0,86	0,84
India	80,0	203,0	2517	1606,3	699	446,2	1,00	0,25
Indonesia	7,3	2,3	43	42,6	12	11,8	0,19	0,59
Iceland	1469,0	1791,0	20170	23813	5603	6615,3	0,44	0,42
Italy	325,8	606,6	3774	7554	1048	2098,5	0,37	0,39
Jordan	153,3	153,3	1540	1540	428	427,8	032	0,32
Canada	377,6	461,0	1023	2546	284	707,3	0,09	0,18
Caribbean	0,1	0,1	1	2,8	0	0,8	0,62	0,89
Kenya	1,3	10,0	10	79,1	3	22	0,25	0,25
China	2814,0	3687,0	31403	45373	8724	12604,6	0,35	0,39
Colombia	13,3	14,4	266	287	74	79,7	0,63	0,63
South Korea	51,0	16,9	1077	75,2	299	48,7	0,67	0,33
Lithuania	21,0	21,3	599	458	166	127,2	0,90	0,68
Macedonia	81,2	62,3	510	598,6	142	166,3		0,30
Mexico	164,2	164,7	3919	1931,8	1089	536,7	0,76	0,37
Nepal	1,1	2,1	22	51,4	6	14,3	0,66	0,78
The Netherlands	10,8	253,5	57	685	16	190,3	0,17	0,09
Germany	397,0	504,6	1568	2909,8	436	808,3	0,13	0,18
New Zealand	307,9	308,1	7081	7086	1967	1968,5	0,73	0,73
Norway	6,0	450,0	32	2314	9	642,8	0,17	0,16
Peru	2,4	2,4	49	49	14	13,6	0,65	0,65
Poland	68,5	170,9	275	838,3	76	232,9	0,13	0,16
Portugal	5,5	30,6	35	385,3	10	107	0,20	0,40
Russia	307,0	308,2	6132	6143,5	1703	1706,7	0,63	0,63
Romania	152,4	145,1	2871	2841	797	789,2	0,60	0,62
Serbia	80,0	88,8	2375	2375	660	659,8	0,94	0,85
Slovakia	132,3	187,7	2118	3034	588	842,8	0,51	0,51
Slovenia	42,0	48,6	705	712,5	196	197,9	0,53	0,46
The USA	5366,0	7817,4	20302	31239	5640	8678,2	0,12	0,13
Thailand	0,7	1,7	15	28,7	4	8	0,68	0,54

Table 2 (ending)

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Tunisia	19,7	25,4	174	219,1	48	60,9	0,28	0,27
Turkey	820,0	1177,0	15756	19623,1	4377	5451,3	0,61	0,53
Hungary	328,3	694,2	2825	7939,8	785	2205,7	0,27	0,36
Ukraine	45,5	6,3	495,8	68,7		0,4		0,35
Philippines	1,0	3,3	25	39,5	7	11	0,79	0,38
Finland	80,5	260,0	484	1950	134	541,7	0,19	0,24
France	326,0	308,0	4895	5195,7	1360	1443,4	0,48	0,53
Croatia	113,9	114,0	555	681,7	154	189,4	0,15	0,19
The Czech Republic	12,5	204,5	128	1220	36	338,9	0,33	0,19
Chile	0,4	8,7	7	131,1	2	36,4	0,55	0,48
Switzeland	547,3	581,6	2386	4229,3	663	1174,9	0,14	0,23
Sweden	377,0	3840,0	4128	36000	1147	10000,8	0,35	0,30
Japan	257,5	413,4	5836	5161,1	1621	1433,8	0,72	0,40
Total	162563	273293	162504,8	258839,7	45008	71868,9	27,41	24,09

Describing the development of the world geothermal energy as an integral part of renewable energy in the longer term, we note the following. The share of renewable energy in the global energy production is projected to decline in 2030 (down to 12,5% comparing to 13,8% in 2000). The energy of the sun, wind and geothermal waters will develop at an accelerated rate, increasing annually by an average of 4,1%.

3. Ukraine geothermal energy potential

Regarding the prospects for the development of Ukrainian geothermal energy, it should be noted that Ukraine has identified six priority areas for the development of geothermal energy:

- the creation of geothermal stations for heat supply of cities, settlements and industrial facilities;
- the creation of geothermal power plants;
- the creation of heat supply systems with underground heat accumulators;
- the creation of drying installations;
- the creation of freezing installations;
- the creation of schemes of geothermal heat supply of greenhouses.

Geothermal resources of Ukraine are primarily thermal waters and the heat of heated dry rocks. In addition, the prospects resources for industrial use include heated groundwater resources that are extracted with oil and gas by existing oil and gas wells[1,2,3,4,5].

One of the promising directions for the development of geothermal energy is the creation of combined energy technology units for obtaining electricity, heat and valuable components contained in geothermal heat carriers.

See below in Table 1.3. the potential of working wells for geothermal energy production in Ukraine is presented.

Table 3

The potential of geothermal resources of existing wells in Ukraine

Regions	Theoretically possible potential of geothermal energy, thousand tons of c. f.	Technically achievable potential of thermal water, thousand tons of c. f.	Economically feasible potential of thermal waters, thousand tons of c. f.
1	*2*	*3*	*4*
The Autonomous Republic of Crimea	804,0	67,0	53,6
Vynnytsia Region	–	–	–
Volyn Region	–	–	–
Dnipropetrovsk Region	–	–	–
Donetsk Region	–	–	–
Zhytomyr Region	–	–	–
Zakarpattia Region	236,0	19,8	17,82
Zaporizhzhia Region	–	–	–
Ivano-Frankivsk Region	79,0	4,9	3,92
Kyiv Region	–	–	–
Kirovohrad Region	–	–	–

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Table 3 (ending)

1	*2*	*3*	*4*
Luhansk Region	–	–	–
Lviv Region	262,0	30,5	24,4
Mykolayiv Region	–	–	–
Odesa Region	47,0	5,5	4,4
Poltava Region	271,0	27,1	18,97
Rivne Region	–	–	–
Sumy Region	674,0	67,4	47,18
Ternopil Region	–	–	–
Kharkiv Region	230,0	23,0	16,1
Kherson Region	312,0	26,0	20,8
Khmelnytsk Region	–	–	–
Cherkasy Region	–	–	–
Chernivtsi Region	–	–	–
Chernihiv Region	864,0	86,4	60,48
Total	*3779,0*	*357,6*	*267,67*

On the example of geothermal circulation system (GCS) in the village Illinka it was found that the operation of the GCS for three heating periods showed the possibility of implementing a method of extracting geothermal heat with back-pumping of spent geothermal coolant for the hydrological conditions of Crimea. Thus, a virtually closed cycle of filtration of the geothermal coolant is implemented, which provides environmental protection from pollution.

The list of geothermal objects on which exploration and development works were carried out at various times is given in Table 4.

Table 4

Geothermal power plants in Crimea on the basis of GCS

Settlement	Capacity, MW	Water temperature, °C	Well flow rate, m^3/hour	Objects of heat supply	Annual fuel economy, tons of c. f.
1	*2*	*3*	*4*	*5*	*6*
village Ilyinka	3,2	57	72	residential settlement	1574
village Syzovka	3,5	61	72	residential settlement	1722
village Novo-Oleksiivka	8,4	53	205	dairy farm, residential settlement	4133
village Kotelnykovo	3,5	65	67	residential settlement	1722
village Trudove	4,5	59	96	greenhouses, hot water supply	2214
village Zernove	2,7	50	72	hot water supply	1328

Table 4 (ending)

1	2	3	4	5	6
village Rivne	6,9	62	139	residential settlement	3395
village Yantarne	4,8	85	65	agro-industrial complex	2361
village P'yatykhatky	6,5	51	167	hot water supply	3198
village Medvedivka	1,5	67	28	kindergarten, residential settlement	738
Total	*45,5*				*22385*

It is known that geothermal power plants require very small land plots, much smaller than those required for power plants of other types. They can be placed on almost any land, including farmland. If only 1% of geothermal energy of Earth's crust (depth of 10 km) could be used, we would have at our disposal an amount of energy that is 500 times greater than all the world's oil and gas reserves.

4. Advantages and disadvantages of using geothermal energy

The main advantage of geothermal energy is the possibility of its use in the form of geothermal water or a mixture of water and vapor (depending on their temperature) for the needs of hot water and heat supply, for generating electricity or for all three purposes simultaneously; its practical inexhaustibility; complete independence from environmental conditions, time of day and year.

Recommended applications for geothermal waters depending on their temperature

Temperature, °C	Applications
more than 140	Electricity generation
less than 100	Heating systems of buildings and constructions
about 60	Hot water supply systems
less than 60	Geothermal heat supply systems for greenhouses, geothermal freezing installations, etc.

Note that, taking into account the advancement of geothermal technologies, these recommendations are being revised toward the use of geothermal waters with increasingly low temperatures for electricity generation. Thus, the developed modern combined schemes of geothermal sources application allow to use for the electricity production the coolants with initial temperatures of 70… 80 °C, which is much lower than the recommended ones (150 °C and above). In particular, the St. Petersburg Polytechnic Institute has created hydrosteam turbines, the use of which at GeoTPP allows to increase the useful capacity of systems by an average of 22%.

The efficiency of thermal water in their complex use significantly increases. At the same time in various technological processes it is possible to achieve the most complete realization of the thermal potential of water, including residual, as well as to obtain valuable components contained in thermal water (iodine, bromine, lithium, cesium, table salt, boric acid and many others) for their industrial use.

One of the biggest disadvantages of geothermal energy is the need to return the wastewater to the underground aquifer. Another disadvantage of using this type of energy is the high mineralization of thermal water of most deposits and the presence of toxic compounds and metals in water, which in most cases eliminates the possibility of discharge of this water into the on-surface natural water systems. The aforementioned disadvantages of the use of geothermal energy lead to the fact that for the practical use of the heat of geothermal water requires considerable investment for well drilling, back injection of waste geothermal water, creating corrosion-resistant thermal equipment.

5. Geothermal energy conversion equipment

5.1 Geothermal power plants

There are two types of geothermal power plants: the first group uses water vapor to generate electricity, the second one uses superheated geothermal water. In the first dry vapor from the well enters the turbine or generator to generate electricity. At other plants, geothermal water with a temperature of more than 190 °C is used. Water naturally rises up the well, comes into the separator, where as a result of the decrease in pressure, a part of it boils and turns into steam. The steam goes to a generator or turbine and generates electricity. This is the most common type of geothermal power plant.

Even more striking is the new GeoTPP revolutionary construction technology Hot-Dry-Rock, developed by Australian GeodynamicsLtd several years ago, which significantly improves the energy conversion of geothermal water into electricity. To confirm the forecasts, wells were drilled at a depth of 4.5 km each, which showed that at this depth the temperature reached the required 270… 300 °C. Work is currently underway to estimate the total geothermal energy reserves at this anomalous point in southern Australia, which is estimated to have a capacity of more than 1 GW, with the cost of that energy being half the cost of wind power and 8…10 times cheaper than solar power.

It is becoming clear today that the considerable scale of development of geothermal energy in the future is possible only in case of obtaining thermal energy directly from the rocks. In this case, in places where dry hot rocks are found, parallel wells are drilled, between which a system of cracks is formed. That is, an artificial geothermal tank is actually formed, where cold water comes with the subsequent obtaining of steam or steam mixture.

5.2 Heat pumps

Heat pumps are environmentally friendly compact and economical heating system installations that produce heat for hot water supply and heating systems for buildings using natural and free soil heat, artesian water, seas, lakes, rivers, air heat, process emissions, etc. by transferring it to a coolant with a higher temperature.

In heat pumps, as well as in freezing instalations, the so-called reverse cycle of heat transfer from a low temperature source to a higher temperature source is carried out. It is necessary to spend some amount of mechanical energy.

Heat pumps can be classified by the following features: operating principle; sources of low-potential heat; the combination of low-potential heat used with the environment heated in heat pumps; types of energy consumed.

6. The technological aspects of the exploration of geothermal resources

Physical capabilities of heat power generation by geological environment (GE) within the territory of Ukraine are evaluated using information on the distribution of thermophysical parameters of GE.

The heat flux density is the amount of heat transferred from the bowels to the surface per unit of time per unit of area. It is measured in mW/m^2 and is determined as the result of the multiplication of a geothermal gradient in a certain depth range by the thermal conductivity of the rocks of that interval. In Ukraine, the heat flux density varies from 25…30 mW/m^2 to 100…110 mW/m^2. Temperatures at a depth of 1 km vary from 20 to 70 °C, and at a depth of 3 km – from 40 to 135 °C. The distribution of heat flows is closely related to the peculiarities of the geological development of the regions and their tectonics. Deep heat flux (DHF) is defined as the observed heat flux, adjusted for numerous close to the surface effects: paleoclimate, groundwater movement with a vertical component, geological structures that cause non-horizontal occurrence of the surfaces of the rock section with different thermal conductivity, young sediments, the accumulation of young sediments, etc. The DHF map shows the distribution of its background (35…50 mW/m^2) and anomalous (60…130 mW/m^2) values in Ukraine.

Utilization of thermal energy from GTPP to generate electricity also has a real socio-economic perspective, despite the small efficiency of thermoelectric elements (3…5% for temperatures up to 120 °C and 6…8% for temperatures up to 250 °C), since during the warm season geothermal energy can switch to maximum electricity generation.

7. The formulas for calculating geothermal heating systems

7.1 The calculation of the efficiency coefficient for different geothermal heat supply systems

A. Open two-pipe geothermal heat supply system with connection of hot water supply systems to the falling pipeline (i.e parallel supply of geothermal coolant for heating and hot water supply).

1. The specific consumption of geothermal water, which comes to 1 MW of estimated heat load, is determined by the formula:

$$G_{\text{Т}}^{\text{пит}} = \frac{10^3}{c} \cdot \left(\frac{Q_{\text{оп}}^{'}}{\delta \cdot t_{\text{оп}}^{'}} + \frac{Q_{\text{г.в}}^{'}}{\delta \cdot t_{\text{г.в}}} \right), \tag{1}$$

where: $Q_{\text{оп}}^{'}$, $Q_{\text{г.в}}^{'}$ denote estimated loads of heating, ventilation and hot water supply, W;

c denotes specific heat of the coolant, J/(kg· °C);

$\delta \cdot t'_{\text{оп}}$, $\delta \cdot t'_{\text{г.в.}}$ denote estimated fluctuations in coolant temperatures in heating, ventilation and hot water systems, °C,

$G_{\text{Т}}^{\text{пит}}$ denote specific geothermal water flow per unit of calculated heat load of the object, kg/J.

2. The share of estimated flow of geothermal water consumed for heating is determined by the formula:

$$\alpha = \frac{Q'_{\text{оп}}}{c \cdot G_{\text{Т}}^{\text{пит}} \cdot \delta \cdot t'_{\text{оп}}}. \qquad (2)$$

The same thing, for hot water we get from the formula:

$$\alpha + \beta + \gamma = 1, \qquad (3)$$

where $\gamma = 1 - \alpha$.

3. The degree of relative use of the maximum load for heating is determined by the formula:

$$Z_{\text{оп}} = \frac{T_{\text{сез}} \cdot \varphi_{\text{ср.відп}}}{8500}, \qquad (4)$$

where: $\varphi_{\text{ср.відп}}$ – average heat release coefficient

The average heat release coefficient is determined by the formula:

$$\varphi_{\text{ср}} = \frac{\left(t_n - t_{\text{з.ср}}\right)}{(t_n - t'_{\text{з}})}, \qquad (5)$$

where: t_n – air temperature in the serviced premises, °C;

$t'_{\text{з}}$- estimated outside air temperature for the design of heating or ventilation systems, °C;

$t, t_{\text{з.ср}}$ – average outside air temperature for the period of operation of heating or ventilation systems, °C.

4. The degree of relative use of the maximum load for heating is determined by the formula:

$$Z_{\text{г.в}} = \frac{5500 \cdot 0{,}35 \cdot T_{\text{сез}}}{8500}. \qquad (6)$$

5. Well exploitation coefficient is determined by the following formulas:

- for heating:

$$\tau_{\text{сверд.оп}} = z_{\text{оп}} \cdot \frac{\left(t_{\text{Т}}^{'} - t_{\text{о}}^{'}\right)}{\left(t_{\text{Т}}^{'} - t_{\text{Т}} - 5\right) - \varphi_{\text{ср.оп}} \cdot \left(t_{\text{о}}^{'} - t_{n} - 5\right)}, \tag{7}$$

- for hot water supply:

$$\tau_{\text{сверд.г.в}} = z_{\text{оп}} \cdot \frac{6800 + 0,2 \cdot T_{\text{сез}}}{8500}, \tag{8}$$

6. The weighted average value of the well exploitation coefficient is determined as follows:

$$\tau_{\text{сверд.об}} = \alpha \cdot \tau_{\text{сверд.оп}} + \gamma \cdot \tau_{\text{сверд.г.в}}, \tag{9}$$

7. The degree of relative increase in the estimated flow rate of the well in general for the object is determined with the known $\tau_{\text{сверд.об}} = 0,23$ for for a semi-bounded layer with $I_{n} = 4,9 - \xi_{\text{об}} = 1,6$.

8. The degree of relative triggering of the temperature difference is determined according to the condition $t_{\text{Г}}^{'} = t_{\text{Т}}^{'} = 100$ °C by the formulas:

- for heating:

$$I_{\text{оп}} = \frac{t_{\text{г}}^{'} - t_{\text{о}}^{'}}{t_{\text{г}}^{'} - 5}, \tag{10}$$

- for hot water supply $I_{\text{г.в}} = 1$ since $t_{\text{г.в}}^{'} = t_{\text{т}}^{'}$.

9. The coefficient of efficiency of geothermal heat supply for this scheme is determined by the formula:

$$\eta_{\text{геот}}^{\text{об}} = (\alpha \cdot I_{\text{оп}} \cdot z_{\text{оп}} + \gamma \cdot I_{\text{г.в}} \cdot Z_{\text{г.в}}) \cdot \xi_{\text{об}} \, . \tag{11}$$

B. Dependent heating system with peak heating of geothermal coolant:

1. The specific consumption of geothermal water, which comes for 1 MW of estimated heat load, is determined by the formula:

$$G_{\text{Т}}^{\text{пит}} = \frac{10^{3}}{c} \cdot \left(\frac{Q_{\text{оп}}^{'}}{\delta \cdot t_{т.г}^{'}} + \frac{Q_{\text{г.в}}^{'}}{\delta \cdot t_{\text{г.в}}^{'}} \right). \tag{12}$$

1. The share of the estimated flow rate of geothermal water will be:

$$\alpha = \frac{Q'_{\text{оп}} \cdot 10^2}{c \cdot G_{\text{Т}}^{\text{пит}} \cdot \delta \cdot t'_{\text{т.г}}}. \tag{13}$$

for hot water supply:

$$\gamma = 1 - \alpha .$$

2. The coefficient of heat release corresponding to the moment of shutdown of the peak heating, is determined by the formula:

$$\varphi_{\text{п.відп}} = \frac{\left(t'_{\text{Т}} - t_{\text{в}} - 5\right)}{(t'_{\text{т.г}} - t_{\text{в}} - 5)}. \tag{14}$$

3. The approximate duration of peak heating T_n is determined by the formula:

$$T_{\text{п}} = \frac{\left(1 - \varphi_{\text{п.відп}}\right)^1 / \text{B}}{\text{A}}, \tag{15}$$

where: A and B are empirical coefficients.

4. The average heat release coefficient is determined by the formula:

$$\varphi_{\text{відп}} = \frac{\left(\varphi_{\text{п.відп}} + \varphi_{\text{к}}\right)}{2 \cdot \varphi_{\text{п.відп}}}. \tag{16}$$

5. The temperature of the waste water corresponding to the moment of shutdown of the peak heating, is determined by the formula:

$$t_{\text{сп}} = \varphi_{\text{п}} \cdot (t'_{\text{о}} - t_{\text{в}} - 5) + (t_{\text{в}} - 5), \tag{17}$$

Well exploitation coefficient while heating is determined by the formula:

$$\tau_{\text{сверд.оп}} = \frac{T_{\text{п}} \cdot 24}{8500} + \frac{(T_{\text{сез}} - T_{\text{п}}) \cdot 24}{8500} \cdot \frac{\varphi_{\text{відп}} \cdot (t'_{\text{т}} - t_{\text{сп}})}{(t'_{\text{т}} - t_{\text{в}} - 5) - \varphi_{\text{відп}} \cdot (t_{\text{сп}} - t_{\text{в}} - 5)}. \tag{18}$$

6. The share of peak heating for heating is determined according to the graphs of Fig. 1.

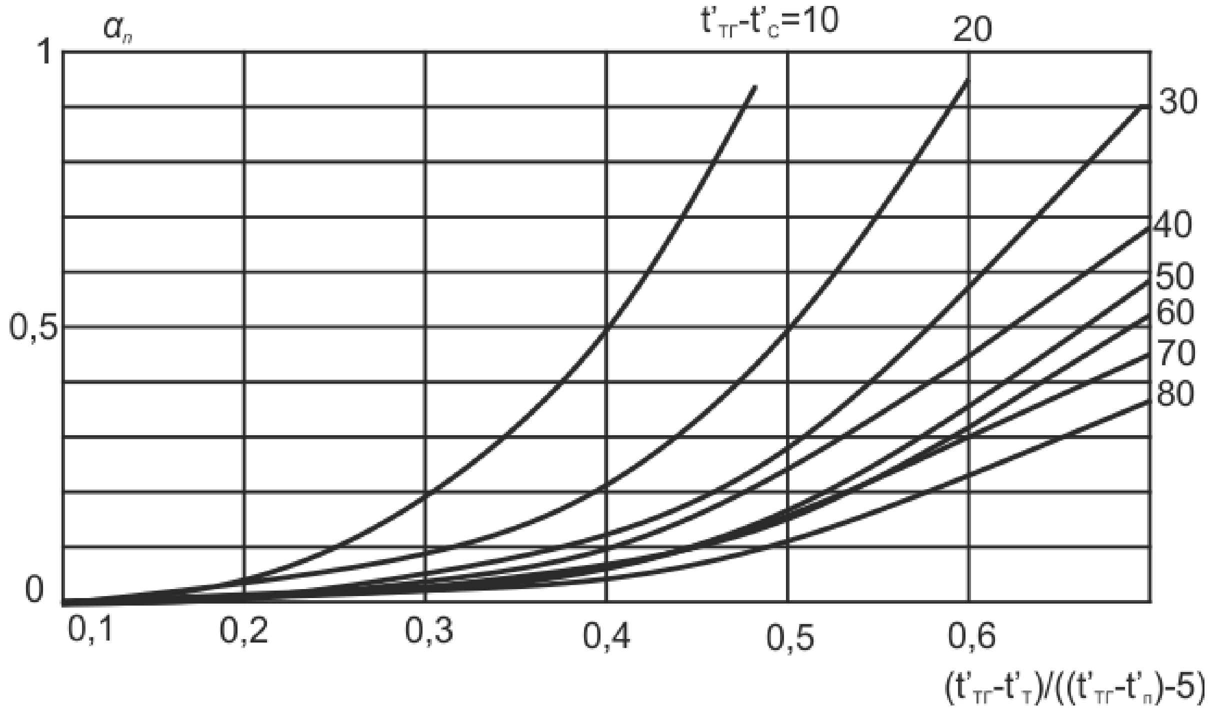

Fig. 1. Graphs for determining the proportion of peak heating during heating

$$\frac{t'_{\text{т.г}} - t'_{\text{т}}}{t'_{\text{т.г}} - t_{\text{п}} - 5}, \tag{19}$$

$$t'_{\text{т.г}} - t'_{\text{о}}, {}^{\circ}C,$$

$$d_{\text{н}} = 0{,}05.$$

7. The degree of relative triggering of the temperature difference is determined by the formulas:

- for heating systems:

$$\frac{t'_{\text{т.г}} - t'_{\text{о}}}{t'_{\text{т}} - 5} \tag{20}$$

- for hot water supply: $I_{\text{г.в}} = 1$.

9. The weighted average value of the well exploitation coefficient is determined as follows:

$$\tau_{\text{сверд.об}} = \alpha \cdot \tau_{\text{сверд.оп}} + \gamma \cdot \tau_{\text{сверд.г.в}}, \tag{21}$$

10. According to the graph of Fig. 2. we determine the value of the index $\xi_{об}$.τ

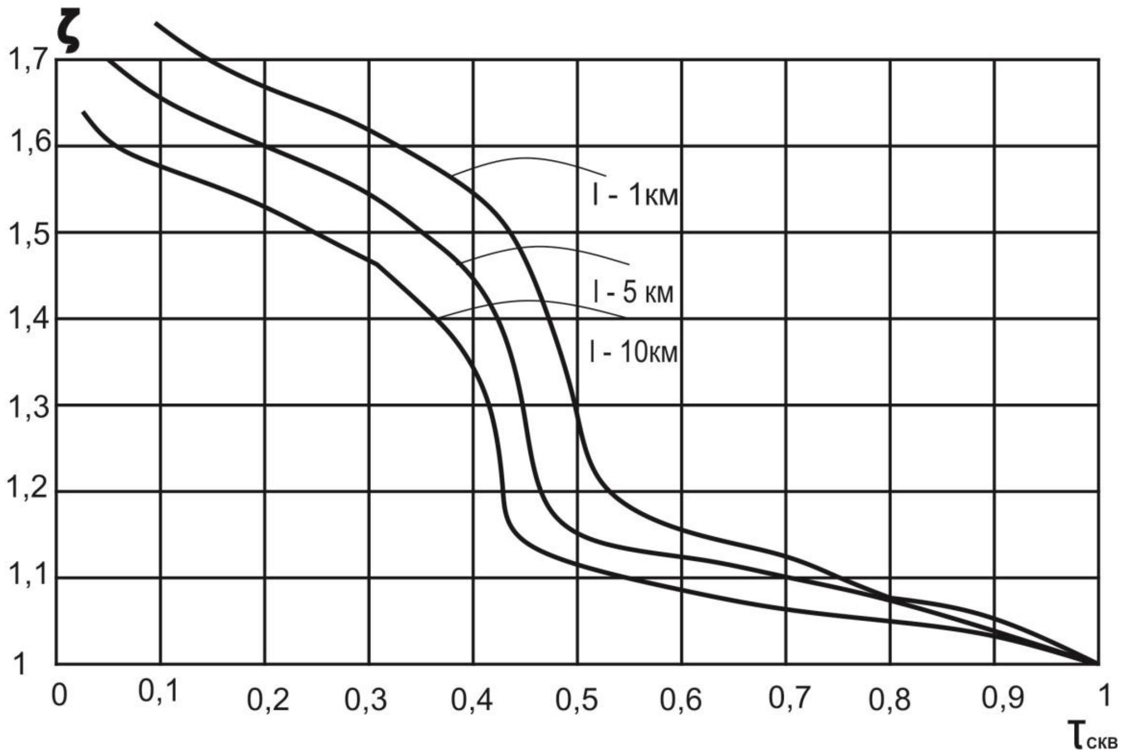

Fig. 2. Graph for determining the degree of relative increase in the calculated flow rate of the heat collection

11. The coefficient of efficiency of geothermal heat supply of the object by the formula is:

$$\mu_{геот}^{об} = (\alpha \cdot I_{оп} \cdot z_{оп} \cdot (1 - d_{н}) + \gamma \cdot I_{г.в} \cdot z_{г.в}) \cdot \xi_{об}. \qquad (22)$$

7.2 The selection of heating devices and the construction of geothermal heating systems' regulation graphs

Below we have an example of calculating the required nominal heat flow of a geothermal heating system device installed in a premise.

1. The calculated degree of triggering of the heat potential of the coolant is determined by the formula:

$$\tau' = \frac{\tau_{г}'' - \tau_{о}''}{\tau_{г}'' - \tau_{п}}. \qquad (23)$$

If τ > 0,4, the calculation should be made according to the following formula:

$$\varepsilon = \frac{\tau_{\text{г}}^{"} - \tau_{\text{о}}^{"}}{\tau_{\text{о}}^{"} - \tau_{\text{п}}}. \tag{24}$$

2. Let us determine the estimated flow use of coolant through the heating device:

$$G_{\text{в}} = \frac{Q}{c \cdot (\tau_{\text{т}}^{"} - \tau_{\text{о}}^{"})}.$$

3. Taking into account the calculated values, choose the type of heating device and by the formula (1.24) we have calculated loads:

$$\varphi_{\text{відп}} = \frac{t_{\text{п}} - t_{\text{н.ср}}}{t_{\text{п}} - t_{\text{н}}}. \tag{25}$$

4. The calculation of the calculated average temperature head is made by the formula:

$$\Delta t_{\text{ср}} = \left\{ \frac{n \cdot \left[(t_{г}^{"} - t_{\text{в}}) - (t_{\text{о}}^{"} - t_{\text{в}}) \right]}{(t_{\text{о}}^{"} - t_{\text{в}})^{-n} - (t_{\text{г}}^{"} - t_{\text{в}})^{-n}} \right\}^{\frac{1}{1,35}}, {}^{\circ}C. \tag{26}$$

5. Determine the values of $\overline{G_n}$ and $\overline{\Delta t_{\text{ст}}}$ by the formulas:

$$\overline{G_n} = \frac{G_{\text{в}}}{0,1}, \tag{27}$$

$$\overline{\Delta t_{\text{ст}}} = \frac{\Delta t_{\text{ст}}}{70}. \tag{28}$$

The nominal heat flow of a heating device to be installed in a premise is determined by the formula:

$$Q_{\text{н}} = \frac{Q}{\overline{\Delta t_{\text{ст}}}^{1,35} \cdot \overline{G_n}^{\text{р}}}, Bm. \tag{29}$$

To construct a graph of quantitative regulation of the heating load, first determine the value χ.

In the next step, we define an indicator characterizing the regulation of the heating load:

$$\overline{G} = \frac{G}{G^{'}} = \varphi \cdot \frac{t_{г}^{"} - t_{в}^{"}}{(t_{г}^{"} - t_{в}) - (t_{о}^{"} - t_{в}) \cdot \varphi}, \quad (30)$$

where: φ – coefficient of heat release for heating; G and $G^{'}$ are current and estimated coolant costs.

The current temperature of the return water is determined by the formula:

$$t_{о} = t_{в} + (t_{о}^{"} - t_{в}) \cdot \varphi, \quad (31)$$

where: $t_{г}^{"}$, $t_{о}^{"}$ - the calculated temperatures of hot and return water in the heat network, °C.

7.3 The calculation of a complex system of geothermal heat supply

Let us define the main technical indicators of a complex system of geothermal heat supply, which provides heating of greenhouses and hot water supply of buildings, which are necessary for technical and economic calculations.

1. Let us set the calculated temperature of tap water after the heat exchanger:

$$t_{г.в}^{р} = t_{о}^{'} - 5, ^{\circ}C. \quad (32)$$

2. The necessary efficiency coefficient of heat exchanger is determined by the formula:

$$\varepsilon = \frac{t_{г.в}^{р} - t_{вод}}{t_{о}^{'} - t_{вод}}. \quad (33)$$

3. KF work, which characterizes the design and size of the heat exchanger is determined by the formula:

$$KF = \frac{c \cdot 10^{3} \cdot G_{г.в}}{\frac{G_{г.в}}{G_{т}^{'}} - 1} \cdot \ln \frac{1 - \varepsilon}{1 - \varepsilon \cdot \frac{G_{г.в}}{G_{т}^{'}}}. \quad (34)$$

4. Installed thermal power of peak heat source:

$$Q_{\text{п}}^{'} = c \cdot 10^{3} \cdot G_{\text{г.в}} \cdot \left[t_{\text{г.в}}^{'} - t_{\text{вод}} - \varepsilon \cdot (t_{\text{о}}^{'} - t_{\text{вод}}) \right], MBm. \tag{35}$$

The value of the heat release coefficient, according to the activation (shutdown) of peak heating, is determined according to the formula:

$$\varphi_{\text{п}} = 1 - \frac{Q_{\text{п}}^{'}}{\varepsilon \cdot c \cdot 10^{3} \cdot G_{\text{г.в}} \cdot (t_{\text{т}}^{'} - t_{\text{о}}^{'})} \tag{36}$$

5. Outside air temperature $t_{\text{ç.ï}}$ is determined by the formula:

$$t_{\text{з.п}} = t_{\text{н}}^{'} + \frac{Q_{\text{п}}^{'} \cdot \left[t_{\text{в}} - t_{\text{н}}^{'} \right]}{\varepsilon \cdot c \cdot 10^{3} \cdot G_{\text{г.в}} \cdot (t_{\text{т}}^{'} - t_{\text{о}}^{'})}, \ {}^{\circ}\text{C}. \tag{37}$$

The annual flow rate of a geothermal coolant can be determined by defining the area constructed on the basis of the adjustment graph $G_T(\varphi)$ by the formula (25).

7.4 The number of extraction and absorption wells

The number of extraction and absorption wells is determined by the amount of geothermal water required and the productivity of one well:

$$n = \frac{Q}{Q_c}, \tag{38}$$

where n is the number of extraction or absorption wells; Q – volume of required production of geothermal water; Q_c – estimated productivity of extraction well.

$$Q_c = \frac{4\pi kmS}{\ln \dfrac{2.25at}{r_c^2}}, \tag{39}$$

where S – reduction in the well (defined as the difference between the pressure at the outlet of the well and the pressure at its intake); k – filter coefficient; m – reservoir power; a – coefficient of piezoconductivity; t – operation time of the geotherm; r_c – well radius.

During the calculations, it must be borne in mind that the extraction wells should be located as close as possible to the consumer, and the absorption wells should be at a distance so as not to affect the temperature regime of the former.

7.5 The calculation of pump power for pumping the coolant into absorption well

Pump capacity is:

$$N = \frac{\gamma QP}{102\eta} \tag{40}$$

where γ is the density of thermal water; Q – geothermal water consumption;

η – Pump efficiency; P – pressure at the inlet of the absorption well.

$$P = \frac{Q_{доб}}{2\pi km}\ln\frac{1.5\sqrt{at}}{r_c}, \tag{41}$$

where Q_{daily} – daily flow of water pumped into the reservoir; k – filter coefficient; m – reservoir power; a – coefficient of piezoconductivity of the collector; t – operating time of the well; r_c – well radius.

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