DEVELOPMENT OF GEOTHERMAL RESOURCES OF MOSCOW ARTESIAN BASIN

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Abstract. The purpose of investigations was to substantiate expediency and ways ofdevelopment ofgeothermal resources in central regions ofthe European territory of Russia Methods of evaluation of geothermal resources have been elaborated and their evaluation for formation thermal waters of Moscow syneclise has been made Total energy of discovered resources is equal to 44 bln tns of conventional fuel Estimate made on the basis of economic-mathematical modelling and feasibility report show that technological-econonuc index numbers of systems ofgeothermal heat supply are comparable with those ones of alternative boiler- houses run on natural gas

Introduction

Needs for heat supply amount to a considerable part in a fuel-energy balance of Russia Search for an alternative to organic fuel which is used for this purpose has been carried out for several scores of years The Earth's heat seems to be one of the most perspective sources of energy to supply heat for rural and urban population of Russia It is proved by well-known advantages of geothermal energy as well as by conditions and a specific character of organization of heat supply in the country [1]

Serious difficulties in obtaining thermal rating are experienced by regions in Central Russia which practically lack their own traditional energy resources At the same time a large sedimentary basin with an area up to 500,000 km^2 - Moscow syneclise with which a geothermal anomaly caused by an upflow of deep heat is connected - corresponds to a considerable part of the 8 regions on this territory

Geothermal characterization of Moscow syneclise

The syneclise is a depressed structure of the East-European platform and is located between the Baltic Shield, Voronezh and Volga- Ural anticlines Sedimentary cover of the syneclise is composed of carbonate and terrigenous deposits from the Vendian to the Mesozoic-Cenozoic

Ageothermal gradient within sedimentary deposits comes to 20-25 sometimes 35^{o}C/1000 m Multiple reservoir horizons saturated with formation water are connected to terrigenous sediments of the cover At least two of them (the Middle Devonian and the Middle Cambrian) are distinguished by increased effective thickness (up to 100-150 m) and permeability (0 3-1 0 D) and can be of practical interest for geothermal heat supply

Aquifers under discussion are a part of Moscow artesian basin Hydrodynamic and hydrochemical zonalities closely connected with each other are clearly seen in the artesian basin The given Middle Devonian and Middle Cambrian horizons are located in a zone of non-circulating water By its composition the water of the Middle Cambrian horizon is a brine of a chloride-sodium type with mineralization of 200-250 g/l Content ofbromine is up to 1 5 g/l and iodine - 2-20mg/l Presence of trace alkaline metals (up to 40 g/l) and boron (up to 16 mgil) has been discovered Potential debit is poorly studied and reaches 900 m^3/24 hours according to calculations The Middle Devonian water is also a brine of a chloride-sodium type with mineralization of 100-250g/l Content of bronune is up to 1 g/l, iodine - 3-12 mg/l Presence of boron and potassium (up to 2 2 g/l), rubidium and other trace elements has been discovered Potential debit of the complex is high, debits of wells are 0 04-0 09 l/s

The Middle Devonian horizon mainly consists of fine-grained quartz sandstones and sands Siltstone and mudstone form rare usually thin (up to 1-2 m) and quickly wedging interbeds Fine-grained sandstone with rare thin interbeds of siltstone and mudstone predominate in the composition ofdeposits under discussion

Geological-geothermal conditions of this structure were obtained while studying materials resulted from testing more than 60 deep wells (L A Pevzner, I F Gorbachev, E S Nikashin, A Ya Chagaev) To obtain generalized characteristics of these two pay horizons a statistic analysis [2] of basic geological-geothermal factors (Table 1) which determine parameters and index numbers of construction and exploitation of systems (stations) of geothermal heat supply (SGHS) was made

Table 1

Statistic characterization of geological-geothermal conditions of the Middle Cambrian horizon of Moscow syneclise

Index numbers	Formation temperature, ^{o}C	Depositional depth, m	Thickness of horizon, m	Permeability, D
Min value	27	1064	25	0.08
Max value	69	2314	68	3.00
Arithmetical mean	47	1687	40	0.93
Dispersion	20.5	1705.11	11.6	1.01
Standard deviation	14.3	413	10.8	1.00
Asymmetry	1.07	-0.069	0.72	1.21
Excess (steepness)	0.50	-1.446	0.95	0.22

On the basis ofmethods developed by SPGGI [3] anticipated (P_1) and perspective (C3) resources of thermal energy of natural reservoirs of two pay horizons of Moscow syneclise were evaluated Anticipated geothermal resources of category P_1 are defined as heat content of a formation with thickness - m, area - S, taking into account a coefficient of temperature extraction - ζ_t and a coefficient of conductive inflow - ζ_k, under conditions of cooling (in the area of a development well) of formation with temperature - Tp down to ambient temperature - t_0

$$Q_p=k*\zeta_t*\zeta_k*C_v*m*S*(T_p-t_0),$$ tons of conventional fuel, (1)

where k - coefficient of conversion of a unit of heat to conventional fuel, tons ofconventional fuel/GJ; C_v- bulk thermal capacity of the rock averaged by formation thickness, J/m^3*^{o}C

Perspective geothermal resources of category C3 are that part of a heat contained formation which can be cost-effectively extracted and used at a modern geothermal technology and market conjuncture An extraction technology and transformation of geothermal energy are based on employment of rock - energy - installations consisting of geothermal circulation systems (GCS) with natural reservoirs and heat pumping units (HPU) A boiler- house run on natural gas is assumed as an alternative source of heat

A coefficient of economic expediency - ratio between specific expenditures for heat production at an alternative boiler-house and specific expenditures of SCHS - is the criteria of econonuc efficiency Basic natural conditions determining economics of extraction of geothermal energy are depositional depth of a reservoir, its thickness, pock permeability and thickness Estimate of resources of category C3 is made according to sinular evaluation of anticipated resources added with a coefficient of envelopment which characterizes filtration flows in a zone of heat extraction and a level of its cooling by the end of an exploitation term

A specific index number of the amount of resources on a territory is assumed to be the density of geothermal resources per a unit of its area

$$q=Q_p/S, \text{ tons of conventional fuel} / m^2 \quad (2)$$

It was calculated for each well where the temperature of an aquifer was no lower than 20°C SGHS heat productivity with an account

– investments for construction of SGHS with heat productivity of 5, 25, 100 *GJ/*h,
– self-cost of delivery of thermal energy,
– profit from realization of 1GJ/h of energy delivered to a customer

This work was made on the basis of economic-mathematical modelling according to developed techniques [4] By the indicated criteria the authors compiled an album of maps which provides a

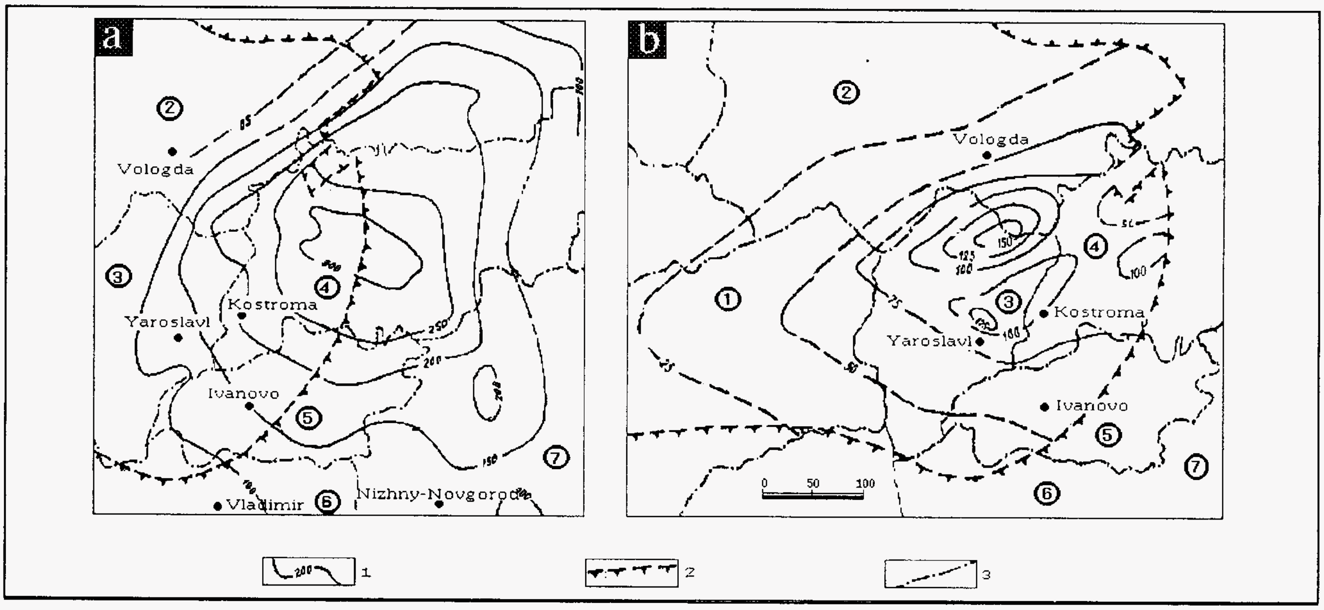

Fig 1 Schematic maps of density of perspective geothermal resources of Moscow syneclise

a) - The Middle Devonian aquifer b) - The Middle Cambrian aquifer
1 - isoline of density of geothermal resources, thou of tons of conventional fuel km² a - real, b - anticipated, 2 - boundaries of extension of the Cambrian horizon,
3 - boundaries of administrative regions 1 - Tver, 2 - Vologda, 3 - Yaroslavl, 4 - Kostroma, 5 - Ivanovo, 6 - Vladimir, 7 - Nizhiiy Novgorod

of mass consumer (small villages, agricultural cooperatives, large farms etc) was assumed to be 5 GJ/h

On the basis of these data maps of perspective resources of geothermal energy of the Middle Devonian and Middle Cambrian horizons (Fig 1) by the method of simple interpolations were made Distribution of perspective resources in administrative regions (Table 2) witnesses their presence on more than 40% of the territory of the central Russia and their total energy potential equals to 33 2 and 10 9 bln tons of conventional fuel for the Middle Devonian and Middle Cambrian aquifers respectively

Table 2

Perspective geothermal resources of thermal aquifers of Moscow syneclise

Administrative regions	Territory with resources				Perspective resources, mln.tns of conv.fuel		Average specific density, thou.tns of con.fuel	
	thou.km²		% of total		Dv	Km	Dv	Km
	Dv	Km	Dv	Km				
Vladimir	14	3	49	11	1420	110	101	36
Vologda	62	51	43	35	8136	2506	133	49
N.Novgorod	28	—	37	—	4200	—	150	—
Ivanovo	24	12	100	49	4063	752	169	63
Kostroma	54	26	90	42	11457	2164	212	83
Novgorod	—	4	—	8	—	106	—	27
Tver	3	51	3	61	189	1994	63	39
Yaroslavl	36	36	100	100	3594	3375	100	94
Total	221	183	—	—	33159	10897		

Dv - the Middle ***Devonian,*** *Km - the Middle Cambrian horizons*

Economic division of geothermal resources of the central regions of Russia into areas within Moscow syneclise was made using a number of criteria
– coefficient of econonuc expediency of development of thermal energy from thermal aquifers,

customer with preliminary data on competitiveness of construction and exploitation of a geothermal facility in the area he is interested in

Division of the territory of Moscow syneclise into areas and its mapping was carried out by a proposed coefficient [5] of econonuc expediency - ratio between specific expenditures for heat production at an alternative boiler-house and expenditures for SGHS It was fulfilled (Fig 2 and Table 3) regarding two categories of thermal needs complete heat supply (90°C) and only hot water supply (60°C)

Table 3

Economic expediency of development of geothermal resources of thermal aquifers of Moscow syneclise

CEE[1]	Distribution of territories of regions by CEE[1], %						
	Vladimir	Vologda	Novgorod	Ivanovo	Kostroma	Tver	Yaroslavl
Hot water supply							
>1.5	—	1/-	3/-	-	29/-	—	—
1.4-1.5	—	16/-	30/-	19/-	53/21	—	-/19
1.3-1.4	—	12/20[2]	22/-	11/30	13/42	-/10	11/71
1.2-1.3	—/34	33/24	19/-	34/38	4/10	-/14	30/5
<1.2	100/66	38/56	26/-	36/32	-/27	100/76	59/5
Complete heat supply							
>1.3	—	6/-	18/-	2/-	69/-	—	—
1.2-1.3	—	22/5	30/-	27/6	28/65	—	6/77
1.1-1.2	-/26	31/25	24/-	31/31	3/7	—	36/18
<1.1	100/74	41/70	28/-	40/63	-/28	100/78	58/5

[1] *Coefficient of economic expediency*
[2] *The Middle Devonian Middle Cambrian horizons (12 20)*

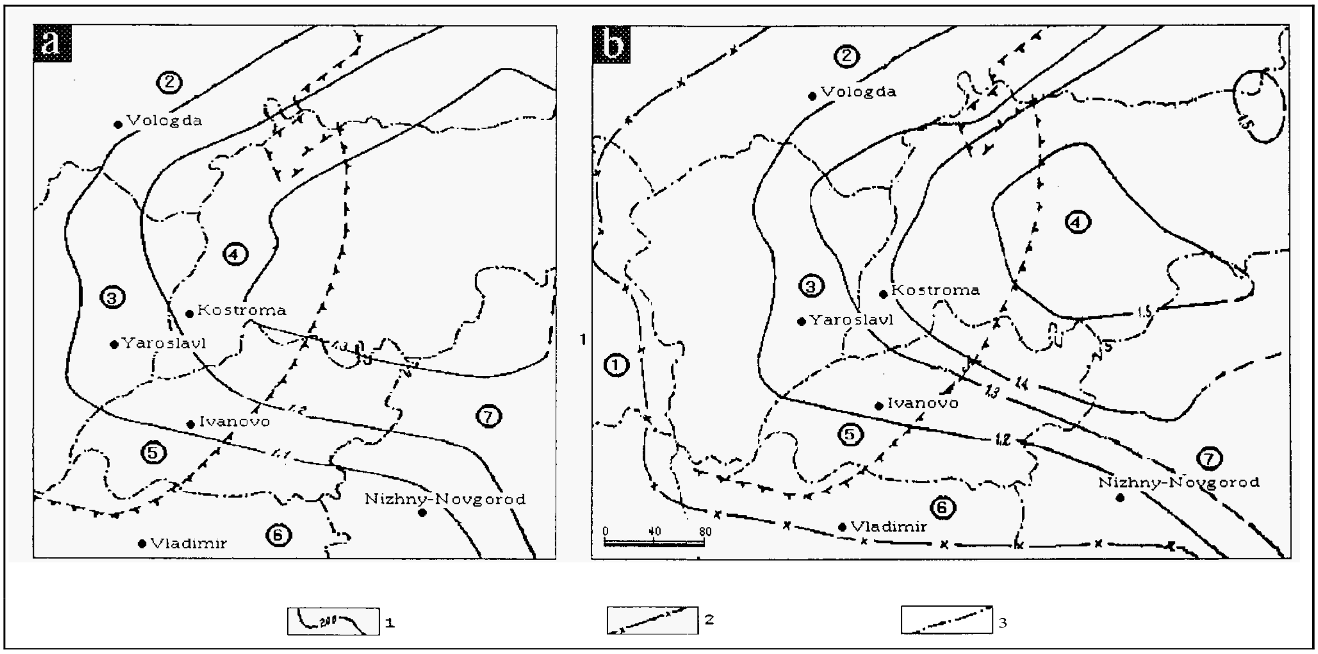

Fig 2 Diagrams of economic expediency of development of geothermal resources of Moscow syneclise (heat supply - 90°C)
a) - The Middle Devonian aquifer,
b) - The Middle Cambrian aquifer
*1 - **isolines** of a coefficient of economic expediency a - real, b - anticipated,*
2 - isotherm of 20°C Other legend is in Fig 2

Economic-mathematical modelling

Geological geothermal characterization ofthermal resources of the Earth in this region as well as on many other territories of Russia requires construction of specific systems (stations) of geothermal heat supply (SGHS) These are rock-energy facilities which provide a customer with heat having preset parameters, regimes and quantities SGHS consists of a production complex - geothermal circulation system (GCS) and ground facilities for heating and transformation of heat transport medium Such a combination of rock-technological and energy systems results in multifactor and complex functional link of conditions and results of operation of this facility Natural conditions, design and technological parameters, operational regimes, economic and social-econonuc factors and limitations are closely connected

Table 4

Basic data and parameters of SGHS (GSC+HPU)

Basic data and parameters	Settlement of Medyaguino	Settlement in Latvia
Max heat productivity, GJ/ h	25	20
Temperature of reservoir rock, °C	56	42
Permeability of reservoir rock, D	0.46	0.48
Reservoir thickness, m	104	73
Depth of development well, m	2190	1540
Price for electricity, USD/ MW*h	50	27
Price for fuel, USD/ tn of conventional fuel	129	109
Index number of recalculation of prices for equipment	1.5	1.3
Well diameter, m	0.15	0.15
Distance between wells, m	400	500
Pressure of pumping out (max), MPa	-0.016	2.31
Injection pressure (max/ min), MPa	7.7/ 3.2	7.3/ 2.1
Well debit (max/ min), m^3/ h	153/ 20	160/ 24
Temperature of produced fluid, °C	52.9	39.9
Service life of GCS module, years	27	27

For systematic optimization of SGHS SPGGI was the first (1971) to develop economic-mathematical models [4] of functioning of this systems at different technologies of production of the Earth's heat and different purposes for its use On the basis of such a model of SGHS which includes GCS with a natural reservoir and heat pump unit (HPU) optinuzational calculations for more than 40 wells drilled on the territory of Moscow syneclise were made SGHS with heat productivity of 5, 25 and 100 GJ/ h was evaluated On a level of a feasibility report there was done some work on preproject evaluation of construction of experimental-industrial SGHS in the village of Medyaguino (near Yaroslavl), the city of Rybinsk and outside Moscow syneclise in a number ofsettlements and cities of Latvia, Lithuania, Ukraine, Pskov region and some other regions of Russia

Some basic data and parameters of SGHS with reservoirs in the Cambrian horizon (Table 4) are given on two settlements located in Yaroslavl region and on the territory of Latvia Havingestimated heat productivity of 25 and 20 GJ/ h and at a temperature schedule of a consumer 90/ 95°C it is quite sufficient to have one GCS module - a pair of wells with a diameter of 150 mm and depths of 2190 and 1540 m It is provided by an optimum debit of development wells during the coldest five-day period - 153 and 160, and

Table 5

Exergetic index numbers of SGHS (GCS+HPU)

Parameters and index numbers	Settlement of Medyaguino	Settlement in Latvia
Annual heat production of SGHS, bln of J/ year	91	69
Fuel saving , thou. of tns of conventional fuel/ year	3.9	2.95
Consumption of electricity by SGHS, GW*h/ year	7.8	7.0
including GCS	0.8	1.4
Fuel consumption, thou. tns of conventional fuel / year[1]	2.7	2.4
Power consumed by SGHS (max),MW	4.3	3.8
Consumption of electricity, kW*h/ GJ	85.7	102.6
including GCS	9.1	20.1
Output of electric boiler-house, tns of conventional fuel/ year[2]	964	865

[1] *Conditional fuel consumption by a thermal power station for generation of electricity spent by SGHS for its own needs*

[2] *Conditional heat output of an electric boiler house at the expense of electricity spent by SGHS for its own needs*

during a period of hot water supply (HWS) - 20 and 24 m^3/h which corresponds to comparatively high transmissivity of reservoirs - 48 and 35 D*m

An energetic analysis of the results of SGHS operation (Table 5) shows that 1 44 and 1 23 tons of conventional fuel are produced per each ton of fuel spent by a thermal power station for generation of electricity consumed by GCS and HPU for their own needs It is not very high efficiency of proposed geothermal facilities but if the given electric power is used to produce heat in electric heaters than there will be produced only 0 36 and 0 29 tons of conventional fuel i e 4 and 4 2 times less

In the econonuc calculations (Table *6)* they used methods of conditional conversion of expenses and index numbers into USD equivalent It allowed the use of world and Latvian prices for fuel and electricity for Russian and Latvian conditions respectively beside that the structure of expenses is given in compliance with world practice

Table 6

Economic index numbers of SGHS (GCS+HPU)

Parameters and index numbers	Settlement of Medyaguino	Settlement in Latvia
Investments for SGHS construction, mln USD	1.550	1.190
including : for GCS	0.815	0.635
for HPU	0.584	0.438
Average self-cost of delivery, USD/ GJ	6.110	5.780
the same for GCS	1.580	2.410
the same for HPU	4.700	3.640
Credit pay of and rate of interest, USD/ GJ	1.150	1.160
Self-cost of heat at a boiler-house, USD/ GJ	8.960	8.240
Coefficient of economic expediency	1470	1 143

Comparatively low investments and production expenditures in comparison with the European ones can be explained by the following factors

- considerably lower level of wages,
- comparatively low cost of drilling wells,
- lower expenditures for manufacture of equipment,
- exclusion of expenses for SGHS renovation from cost-estimate as it is of an experimental-industrial type

Conclusion

1 Energy crisis and ecological struggle create conditions for economically expedient development of geothermal resources in the central regions of Russia

2 With the application of thermal transformers one can successfully develop geothermal fields in low temperature reservoirs of Moscow syneclise

3 Geothermal resources of this region total about 44 bln of tns of conventional fuel at specific density from 30 to 300 thou of tons of conventional fuel/ km^2

4 Technological-economic index numbers of SGHS are comparable with those ones of alternative boiler houses run on natural gas

5 At a comparatively slight exergetic gain of SGHS versus boiler-houses heat production in electric heaters will be 4 times less than at SGHS at the expense of the electric energy spent by the latter for its own needs

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