Thermal power potential assessment of Avacha geothermal system

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Abstract. Thermal power potential assessments of Avacha geothermal system performed by different authors of the works and the methods adopted for evaluation are presented. A significant variation of the predicted thermal and electric power values was established. In order to obtain a more reliable heat and power potential assessment in the present work the authors have developed the thermo-hydromodel of Avacha geothermal system based on the complex of available geological and geophysical data. According to the numerical simulation results, the lower assessment of the system resources is 35 MW, the upper one is 302 MW of thermal power.

1. Introduction
Avacha geothermal system is located in the southeast of Kamchatka Peninsula and is confined to the eponymous active volcano located 25-30 km from Petropavlovsk-Kamchatsky, Russia. The height of the volcano is 2750 m, the volume is 100 km³. The estimated age of the volcano is 60000. For the last 3500 years, a young cone of the volcano has been forming with active fumarole activity. Natural thermal manifestations were formed in the crater of the volcano cone and represented by heated areas, steaming grounds and fumaroles. The complex of explorations conducted from 1960 suggested the presence of molten peripheral magmatic chamber beneath the volcano edifice at a depth of 0–5 km.

Earlier, from 1977 to 2016 various authors carried out prognostic assessments of Avacha geothermal system thermal and electric power, which are summarized in table 1. Some of these assessments were based on the calculation of the heat energy stored in the block of heated rocks located near Avacha volcano peripheral magmatic chamber. As it can be seen from table 1 the lower predicted thermal power is 12 MW, the upper one is 2000 MW, while the lower electrical power is 250 MW and the upper one is 2500 MW. The magnitude difference by a factor of 100 only underlines the rough approximation of performed assessments, resulting from the approximation of the input parameters and methods adopted for the assessments. It is also important to note, that some authors of the references, summarized in table 1, performed the conversion of thermal power into electrical one incorrectly, taking the efficiency of about 50%. It is well known that the maximum total efficiency of modern geothermal power plants (GeoPP) does not exceed 20%.

Beneath, the volumetric method was used to estimate potential geothermal resources of Avacha geothermal system, which involves the volumes determination of a block, a layer or a reservoir of heated rocks, their temperature and specific heat reserves. For the evaluation of rocks potentially expected temperatures within the area of Avacha geothermal system, its numerical thermo-
hydrodynamic modeling was performed. The following calculations are based on the results of thermo-hydrodynamic modeling [9].

**Table 1.** Predictive power assessment of Avacha geothermal system.

| Predictive power, MW | Power assessment method                                                                 | Authors, year, reference |
|----------------------|--------------------------------------------------------------------------------------------|--------------------------|
| 75                   | Based on the heat outflow with fumarolic gases                                              | Fedotov S A et al, 1977, [1] |
| 44                   | Based on the magmatic chamber heat transfer                                                 | Polyak B G and Melekestsev I V, 1981, [2] |
| 60                   | Based on the height of the volcano crater fumaroles plume rise for the period from April to May, 1981 | Fedotov S A, 1982, [3] |
| 523-581              | Based on the estimated heat reserves in the rocks of 50 km³ enclosing the magmatic chamber | Fedotov S A et al, 2007, [4] |
| 12                   | Based on the height of the volcano crater fumaroles plume rise for the period from November 2008 to January, 2009 | Ivanov V V, 2010, [5] |
| 2000                 | Based on the results of thermo-hydrodynamic modeling of Avacha geothermal system and geothermal circulation system | Pashkevich R I et al, 2016, [6] |
| 2500                 | Based on the heat extraction from rocks of 25 km³ heated by the magmatic chamber to temperature 600°C | Sugrobov V M, 1976, [7] |
| 250                  | Based on the estimated heat reserves in the rocks of 50 km³ enclosing the magmatic chamber | Fedotov S A et al, 2007, [4] |
| 1400                 | Based on the available drilling area, heat outflow and COP                                  | Pashkevich R I and Trukhin Yu P, 2014, [8] |

**2. Numerical thermo-hydrodynamic model**

The numerical model is based on HYDROTHERM software package designed for 3D simulation of multi-phase ground-water flow and associated thermal energy transport in porous medium in the range of temperature and pressure 0-1200°C and 0.05-1000 MPa respectively, including supercritical thermodynamic state of water. Mathematical model is based on the equations systems of mass and energy conservation, expressed in terms of the pressure and enthalpy units [10,11]:

\[
\frac{d}{dt}\left[\phi (\rho_w S_w + \rho_s S_s)\right] - \nabla \cdot \left[ k_{rw} \rho_w \left( \nabla p - \rho_s g \right) \frac{k_{s_s}}{\rho_s} \left( \nabla p + \rho_s g \right) \right] - q_{sf} = 0
\]

\[
\frac{d}{dt}\left[ (1-\phi) \rho_f h_f + \phi (s_w \rho_w h_w + s_s \rho_s h_s) \right]
\]
where $\phi$ is the porosity; $\rho_w$, $\rho_s$, $\rho_r$ are the water, steam and rocks densities respectively; $k_{rw}$, $k_{rs}$ are the relative phase permeability of water and steam respectively; $\mu_w$, $\mu_s$ are the dynamic viscosity of water and steam respectively; $K_i$ is the effective thermal conductivity of the bulk porous medium; $h_w$, $h_s$, $h_r$ are the water, steam and rocks enthalpy respectively; $I$ is the identity matrix of rank 3, $q_{sf}$ and $q_{sh}$ are and the flow-rate intensity of a fluid-mass source and an enthalpy source, respectively.

Computational grid was developed in HYDROTHERM preprocessor and the modeling results visualization was performed in TECPLOT software package.

Based on the interpretation of geological and seismic data (figure 1), a three-dimensional conceptual model comprising 9 domains (rock layers) and a magmatic chamber (figure 2) was developed. An irregular computational grid was used, with dimensions of the smallest blocks of 300×300 m in the area close to the magmatic chamber. In plane the modeling area is limited by a rectangle of 236.6 km² (figure 3), the model depth with considering the volcano edifice is 8 km. The model consists of 33800 blocks. The boundaries of the model are set to be impermeable, with a thickness of 50 m.

**Figure 1.** Seismic section along deep seismic sounding (DSS) profile [12]. 1 – velocity boundaries (a) and located cretaceous basement boundary (b); 2 – reflecting layers; 3 – earthquakes epicenters for the periods of 1994 and 1997; 4 – diffraction points; 5 – zones of seismic waves velocities anomalies (B) and waves absorption (A); 6 – $V_p$ waves velocities determined by seismic tomography method.

**Figure 2.** Conceptual model section, its domains and magmatic chamber. Circles are the earthquakes epicenters for the periods of 1994 and 1997 according to seismic section data by Moroz Yu F and Gontovaya L I (figure 1) [12].

At the initial time the average geothermal gradient of 30°C/km and the hydrostatic distribution of the fluid pressure were set in the surrounding magmatic chamber rocks. The constant temperature of
10°C and the atmospheric pressure were set at the upper boundary of the model. The constant heat flux of 120 mW/m² was set at the lower boundary. At the lateral boundaries of the simulation area the condition of no-flow was specified. The temperature of constant convecting magma in the chamber was set in the range of 700-1000°C. Modeling area section, initial and boundary conditions are shown in figure 4.

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**Figure 3.** Geometrical dimensions and computational grid of the model (top view). \( j=13 \) – vertical section of the model.

**Figure 4.** The numerical model section, its domains, initial and boundary conditions. Ellipse – magmatic chamber; 1-9 – domains (layers of rocks) numbers; \( q \) – regional heat flux; \( Q \) – boundary mass flow rate; \( T, P \) – temperature and pressure, respectively; \( P_{\text{atm}}, P_{\text{hyd}} \) – atmospheric and hydrostatic pressure, respectively; \( \Delta T \) – geothermal gradient; \( k=12 \) – horizontal section of the model.
In [13] the heat balance of the magmatic chamber and its feeding channel is considered to find the relationship between the size, temperature and chamber magma flow rate. Using the complex of known data and adopting the thermal regime of Avacha volcano being quasi-stationary, the author [13] calculated the dependences of the temperature of a magma flowing into the chamber and the temperature of the magmatic chamber boundaries for different values of the peripheral chamber radius. The temperature of magma flowing into the chamber was taken in the range of 1020-1200°C, the peripheral chamber temperatures were 900 and 1000°C. The most permissible calculated value of the average focal radius was no more than 2.2 km. With the volcano volume of 100 km³ the maximum possible value of the calculated radius was 4.2 km. With the horizontal axis of 5.2 km obtained by geophysical methods the chamber volume was ~ 240 km³. This upper radius assessment seems excessively high. The lower assessments of 2.6 – 3.6 km are close to the values obtained by the author of [13] in the thermal calculations.

Based on the geological and geophysical summary data, in [4] it was concluded that the magmatic chamber has the shape of the ellipsoid with a ratio of the vertical and horizontal semiaxis lengths of about 1/1.5 and has dimensions of at least 1.53 and 2.3 km, respectively, at the chamber boundary temperature 900°C. According to the geophysical researches, the horizontal semiaxis of the ellipsoid heated plastic zone was estimated at 5 km and the most heated part was 3.6 km [14].

In the numerical experiments the magmatic chamber has the shape of the vertical rotation ellipsoid with horizontal and vertical semiaxes dimensions of 2.25 km and 1.5 km, respectively. This ratio of semiaxes lengths (1/1.5) corresponds to the conclusions in [4]. Thus, adopted semiaxes values can be considered to be the lower limit of Avacha volcano magmatic chamber estimated size. Calculations were performed based on three values of magmatic chamber boundaries temperature: 700, 900 and 1000°C.

Based on the geological profile data [15], each model domain (layer of rocks) has different hydrogeological and thermal physical properties corresponding to the average values for volcanic rocks of Kamchatka [16, 17]. The rocks hydrogeological and thermal physical properties assigned in the modeling are summarized in table 2.

The main types of crustal heat transfer are convection and conduction. Conduction prevails at rocks permeability less than 10⁻³ mD. Given that the actual hydrogeological conditions and rocks parameters within the geothermal system are unknown, the calculations were based for two above mentioned heat transfer types.

The case of convective model was realized by several orders permeability increasing of the edifice rocks (domains 1, 2, 9), as well as of domain 3 (figure 4). Domain 3 was adopted in the model as a highly-fractured zone based on the earthquake epicenters distribution data for the periods 1994 and 1997. The rocks permeability of the model was assumed to be isotropic. The permeability values of the model domains adopted in the simulation are summarized in table 3.

### 3. Numerical simulation results

#### 3.1. Conductive model

Around the magmatic chamber, with the exception of the upper part, a zone of supercritical fluid develops (figure 5). A superheated steam zone of about 1 km wide forms near the top surface of the chamber. Magmatic chamber temperature increase leads to the expansion of supercritical fluid and superheated steam areas. There is a more intense surrounding rocks heating and geothermal gradient increases in the edifice rocks. The magmatic chamber temperature field has a significant influence at a distance of about 5 km, and at a distance of 12-14 km it does not affect the regional geothermal field, that is according with the data of [15] obtained from the temperature measurements in GK-2a well located at 14 km distance from Avacha volcano.

#### 3.2. Convective model

A superheated steam zone develops near the top surface of the chamber, similar to the conductive model case (figure 6). Due to edifice rocks permeability increase the superheated steam at the upper boundary partially condenses, forming a two-phase region. There is a greater rocks heating in the
Table 2. Hydrogeological and thermal physical properties of Avacha geothermal system model domains.

| Domain number | Geological settings | Type of rocks | Porosity | Density, kg/m$^3$ | Thermal conductivity, W/m·K | Specific heat capacity, kJ/kg·K |
|---------------|---------------------|---------------|----------|------------------|---------------------------|-------------------------------|
| 1             | Quaternary          | Middle and Upper Andesits, basalts and its tuffs | 0.07     | 2600             | 1.6                        | 1                             |
| 2             | Paleogene and Neogene Upper miocen-pliocen Alneyskaya series Andesits, basalts and its tufts and tuffits | 0.01 | 2500 | 2.7 | 1 |
| 3$^a$         | Paleogene and Neogene Upper miocen-pliocen Alneyskaya series Andesits, basalts and its tufts and tuffits | Siliceous slates, aleanuropelite, psammitic tuffites, tufts, porphyrites | 0.05 | 2600 | 2.0 | 0.9 |
| 4             | Cretaceous          | Iruney suite  | Siliceous slates, aleanuropelite, psammitic tuffites, tufts, porphyrites | 0.01 | 2650 | 2.7 | 0.9 |
| 5$^b$         | --                  | --             | --       | 0.07             | 2650                      | 2.7                           | 0.9 |
| 6             | Cretaceous          | Hozgon suite  | Banded sandstones, phyllites | 0.01 | 2700 | 2.7 | 0.9 |
| 7             | --                  | --             | --       | 0.07             | 2700                      | 2.7                           | 0.9 |
| 8             | --                  | --             | --       | 0.01             | 2700                      | 2.7                           | 0.9 |
| 9             | Quaternary          | Middle and Upper Andesits, basalts and its tufts | 0.05 | 2600 | 2.0 | 0.9 |

$^a$ Earthquakes epicenters zone for periods 1994 and 1997

$^b$ Zones of seismic waves velocities anomalies and waves absorption

highly-fractured zone (domain 3). Thus, the rocks with temperature 200–400°C can be located at a depth of 1.5–2 km from the surface and at a distance of up to 3 km from the chamber. The increased permeability of the volcano edifice rocks has a cooling effect, which causes geoisotherms «pressing» over the chamber. A similar effect is observed at the boundaries of the near-chamber zone and highly-fractured zone. The magmatic chamber temperature increase leads to the expansion of the supercritical fluid zone near the lateral boundaries of the chamber. At the upper boundary a two-phase region extends. In the highly-fractured zone the area of rocks with temperature 200–400°C enlarges. The value of geothermal gradient in the volcano edifice does not change.

Table 3. Permeability values of Avacha geothermal system model domains.

| Model type | Domain number | Permeability, mD |
|------------|---------------|------------------|
| Conduction | 1             | 0.001            |
| Convection | 2             | 0.001            |
|            | 3             | 0.001            |
|            | 4             | 0.001            |
|            | 5             | 0.001            |
|            | 6             | 0.001            |
|            | 7             | 0.001            |
|            | 8             | 0.001            |
|            | 9             | 0.001            |
| Convection | 5             | 5                |
|            | 6             | 1                |
|            | 7             | --               |
|            | 8             | --               |
|            | 9             | 0.001            |
|            | 0.001         | 0.001            |
|            | 0.001         | 0.001            |
|            | 0.001         | 0.001            |
|            | 0.001         | 0.001            |
|            | 0.001         | 0.001            |
|            | 0.001         | 0.001            |
|            | 0.001         | 0.001            |
|            | 0.001         | 0.001            |
|            | 0.001         | 0.001            |
Figure 5. Pressure (P), temperature (T) and thermodynamic phase (colour) distribution in a conductive model with the magmatic chamber temperature 700°C (a), 900°C (b), 1000°C (c) after 60 000 years of modeling. Slices \( j=13 \) and \( k=12 \) are the vertical and horizontal sections cross the magmatic chamber center, respectively. On the vertical axis there is a depth in km (for slice \( j=13 \)) and width (for slice \( k=12 \)), on the horizontal - width in km.

Figure 6. Pressure (P), temperature (T) and thermodynamic phase (colour) distribution in a convective model with the magmatic chamber temperature 700°C (a), 900°C (b), 1000°C (c) after 60 000 years of modeling.

For the assessment of heat amount accumulated by the rocks surrounding the magmatic chamber during the period of its existence, the conductive model simulation results with the magmatic chamber boundaries temperature 1000°C were used. The volume of the toroid, which size is bounded by the planes at a depth of 0 and 4 km and by the lateral surfaces of 200 and 400°C isotherms, was estimated (figure 7). The toroid was formed by the rotation of a curvilinear trapezoid of 5 km² area along the vertical axis. Thermal power potential \( W_{\text{th}} \) of the pointed rocks block was calculated in equation (3):

\[
W_{\text{th}} = \rho \cdot c \cdot V \cdot \Delta T / \tau \tag{3}
\]

where \( \rho \) is the rocks density assumed as 2600 kg/m³; \( c \) is the specific heat capacity assumed as 1000 J/kg·°K; \( V \) is the volume of the rocks block with temperature 200–400°C calculated as a sum of the computational blocks volumes and amounted to 110 km³ (toroid volume); \( \Delta T \) – temperature drawdown of the rocks block assumed as 1°C, achieved during exploitation time \( \tau \) assumed as 30 years.
### Table 4. Avacha geothermal system thermal power potential assessment based on the magmatic chamber boundaries heat flux.

| Rock blocks coordinates | Thermal power, kW | Rock blocks coordinates | Thermal power, kW | Rock blocks coordinates | Thermal power, kW |
|-------------------------|-------------------|-------------------------|-------------------|-------------------------|-------------------|
| j  i  k                 |                   | j  i  k                 |                   | j  i  k                 |                   |
| 30  14                  | 462.05            | 29  17                  | 192.48            | 25  12                  | 5.701             |
| 29  13                  | 457.76            | 28  16                  | 66.431            | 25  11                  | 439.9             |
| 6  29  12               | 5.58              | 27  16                  | 188.07            | 26  10                  | 268.4             |
| 29  11                  | 440.88            | 26  15                  | 179.71            | 16  27  9               | 212               |
| 30  10                  | 425.96            | 25  14                  | 271.68            | 28  8                   | 251.9             |
| 29  15                  | 418.2             | 25  13                  | 148.07            | 29  8                   | 58.72             |
| 28  14                  | 396.73            | 25  12                  | 2.3163            | 30  7                   | 278.4             |
| 28  13                  | 239.74            | 25  11                  | 147.34            | 29  16                  | 275.37            |
| 7  28  12               | 3.8264            | 25  10                  | 271.92            | 28  15                  | 146.15            |
| 28  11                  | 232.8             | 26  9                   | 191.29            | 27  14                  | 166.01            |
| 28  10                  | 379.51            | 27  8                   | 208.03            | 27  13                  | 98.23             |
| 28  9                   | 372.3             | 28  8                   | 67.022            | 17  27  12              | 1453.33           |
| 30  16                  | 332.47            | 29  17                  | 191.26            | 27  10                  | 161.17            |
| 29  15                  | 78.225            | 29  16                  | 66.095            | 28  9                   | 125.87            |
| 28  14                  | 347.48            | 27  16                  | 186.11            | 29  8                   | 243.79            |
| 27  13                  | 397.58            | 26  15                  | 175.91            | 30  16                  | 343.59            |
| 8  27  12               | 4.0661            | 25  14                  | 265.09            | 29  15                  | 80.115            |
| 27  11                  | 247.12            | 25  13                  | 144.62            | 28  15                  | 351.91            |
| 27  10                  | 385.49            | 25  12                  | 2.2581            | 27  14                  | 399.46            |
| 13  28  9               | 311.88            | 25  11                  | 143.97            | 27  13                  | 253.75            |
| 29  9                   | 63.603            | 25  10                  | 264.64            | 18  27  12              | 4.0724            |
| 30  8                   | 297.1             | 26  9                   | 184.79            | 27  11                  | 247.38            |
| 29  16                  | 268.45            | 27  8                   | 201.57            | 27  10                  | 385.74            |
| 28  15                  | 144.31            | 28  8                   | 64.664            | 28  9                   | 311.99            |
| 27  14                  | 165.08            | 29  7                   | 186.86            | 29  9                   | 63.614            |
| 27  13                  | 98.027            | 29  17                  | 194.02            | 30  8                   | 297.16            |
| 9  27  12               | 1.4506            | 28  16                  | 66.796            | 29  15                  | 424.43            |
| 27  11                  | 95.994            | 27  16                  | 188.64            | 28  14                  | 398.47            |
| 27  10                  | 161.08            | 26  15                  | 179.96            | 28  13                  | 240.03            |
| 28  9                   | 125.82            | 25  14                  | 271.83            | 19  28  12              | 3.83              |
| 29  8                   | 243.72            | 25  13                  | 148.1             | 28  11                  | 232.94            |
| 30  17                  | 278.72            | 25  12                  | 2.3168            | 28  10                  | 379.67            |
| 14  28  16              | 69.026            | 25  11                  | 147.37            | 29  9                   | 372.35            |
| 28  16                  | 275.61            | 25  10                  | 271.95            | 30  14                  | 464.16            |
| 27  15                  | 235.66            | 26  9                   | 191.31            | 29  13                  | 458.12            |
| 26  14                  | 282.74            | 27  8                   | 208.05            | 20  29  12              | 5.5803            |
| 25  13                  | 444.13            | 28  7                   | 67.028            | 29  11                  | 440.84            |
| 10  25  12              | 5.6959            | 29  7                   | 192.08            | 30  10                  | 425.83            |
| 25  11                  | 439.58            | 28  8                   | 253.19            | 28  16                  | 91.727            |
| 26  10                  | 268.28            | 27  9                   | 211.9             | 27  16                  | 347.94            |
| 28  8                   | 251.79            | 26  9                   | 328.23            | 25  14                  | 397.03            |
| 29  8                   | 58.708            | 26  15                  | 159.63            | 25  13                  | 160.71            |
| 30  7                   | 278.34            | 25  12                  | 2.5291            | 25  12                  | 2.5291            |
| 15  29  17              | 279.88            | 29  17                  | 289.1             | 30  17                  | 289.1             |
| 28  16                  | 90.708            | 25  11                  | 159.63            | 27  8                   | 76.625            |
| 27  16                  | 345.57            | 26  9                   | 400.18            | 16  26  15              | Total 34.57 MW    |
| 26  15                  | 327.12            | 26  9                   | 297.61            | 25  14                  | 311.36            |
| 25  14                  | 396.43            | 27  8                   | 76.625            | 28  8                   | 283.7             |
| 25  13                  | 160.63            | 28  8                   | 76.625            | 29  7                   | 278.14            |
According to equation (3) the thermal power potential assessment is 302 MW. This value of potential assessment is based on the assumption of possible initial temperature rocks reducing by a given value during the specified exploitation period. The development and exploitation are supposed to be done by Enhanced geothermal system (EGS) technology. The above mentioned potential assessment method is essentially non-stationary and has a large approximation.

Additional thermal power potential assessment can be performed based on the magmatic chamber boundaries stationary heat flux which formed at the end of the natural state simulation time. For the conductive model and magmatic chamber boundaries temperature of 1000°C the calculation of the magmatic chamber frontal surface segment heat flux, facing south-west, is presented in table 4. The heat flux was calculated using the value for each rocks block located on the magmatic chamber boundary. The values are contained in the output file "Out_bcflow2" of the model. This method of assessment gives the thermal power potential value of 35 MW.

Figure 7. The estimated location of the rocks high-temperature zone prospective for development and exploitation in case of a conductive model.

4. Conclusions
By the complex of available geological and geophysical data the thermo-hydrodynamic model of Avacha geothermal system was developed. Based on the modeling results the assessment of the system thermal and power potential was performed using two methods. The volumetric method which involves the determination of the rocks block volume and its temperature gives the thermal power assessment of 302 MW. The method based on the calculation of the magmatic chamber frontal surface segment heat flux, facing south-west, gives the assessment of 35 MW. Thus, based on the performed calculations, derived from the numerical thermo-hydrodynamic simulation results, the lower assessment of thermal power potential of Avacha geothermal system is 35 MW, and the upper one is 302 MW.

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