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NUMERICAL SIMULATION OF EXPLOITATION OF SUPERCRITICAL ENHANCED GEOTHERMAL SYSTEM

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ABSTRACTS

The process of heat transfer during the fluid filtration in rocks of magma-geothermal system of Mutnovsky volcano was studied by the method of numerical simulation. The distribution of temperature, pressure, fluid phase state and its phases' velocities were obtained. The character of dependence of the calculated geothermal gradient and geometry of supercritical fluid region on the form of magma chamber, the permeability of fluid-conductive zone and degassing discharge was determined.

INTRODUCTION

Recently the magma geothermal systems are discussed as potential objects for development. In depth of such systems the supercritical fluid exists with the temperature above 400^{o}C and the pressure above 22 MPa. The development can be realized by circulating technology, called HDR/EGS technology. There are few supercritical EGS simulations (Yano and Ishido, 1998, Watanabe et al., 2000, Brikowski, 2001, Croucher and O'Sullivan, 2008). In these papers the calculations were accomplished in a narrow range of the parameters and without determination of the rational distance between injectors and producers (*L*, fig. 1) and relative height injector bottom above the producer bottom (H_r).

The response to the exploitation of deep supercritical geothermal reservoir with initial temperature 375–400^{o}C was numerically researched in (Yano and Ishido, 1998) with STAR simulator use (Pritchett, 1995). The operation of single producer was simulated. The calculations were made in a short exploitation time 0.1 year. The STAR simulator has the upper parameter limit of 1000 bar and 800^{o}C. The simulation of the operation of duplet (one injector and one producer) in the reservoir with volume 100x100x100 m with the single fracture and well distance 25 m is presented in (Watanabe et al., 2000). The "five-spot" (four injectors and one producer) TOUGH2 problem (Pruess et al., 1999) was extended in the supercritical conditions with small producer rate 0.9 kg/s in (Brikowski, 2001). Another supercritical version of TOUGH2 was developed in (Kissling and White, 1999). Recently Croucher and O'Sullivan (2008) have presented a new supercritical TOUGH2 version and comparison of their results for supercritical "five-spot" problem with results of (Yano and Ishido, 1998), (Brikowski, 2001) and Kissling (Croucher and O'Sullivan, 2008).

The HYDROTHERM (Hayba and Ingebritsen, 1994, Kipp, 2008) correctly simulates up to 1200^{o}C and 1 GPa and was used in more than 30 simulations of deep hydrothermal, volcano and magma geothermal systems with supercritical conditions. The HYDROTHERM versions 2.2 and 3.0 were used in the present paper.

The comparison of HYDROTHERM ver. 3.0 results for supercritical "five-spot" problem obtained by the authors with the supercritical TOUGH2 results of (Brikowski, 2001) and (Croucher and O'Sullivan, 2008) is presented in Fig. 1. In the reservoir of Fenton Hill project (1975-1995, USA) which created by subvertical fractures the injector bottom was 100 meters deeper producer one. In the current research Soultz HDR project (Ledru, 2007) and commercial Cooper Basin HFR project (Vörös, 2007) the well pattern with H_r=0 is accepted. For the case of subcritical EGS the influence of *L* on the heat mining efficiency was researched by TOUGH2 simulations in (Sanyal and Butler, 2005) but the role of H_r was not discussed.

NUMERICAL MODEL

In the present paper the results of numerical modeling of operation of triplet well pattern (one injector and two producers, Fig. 2) is discussed. The initial temperature in well bottoms is 380^{o}C, pressure is 22.5 MPa.

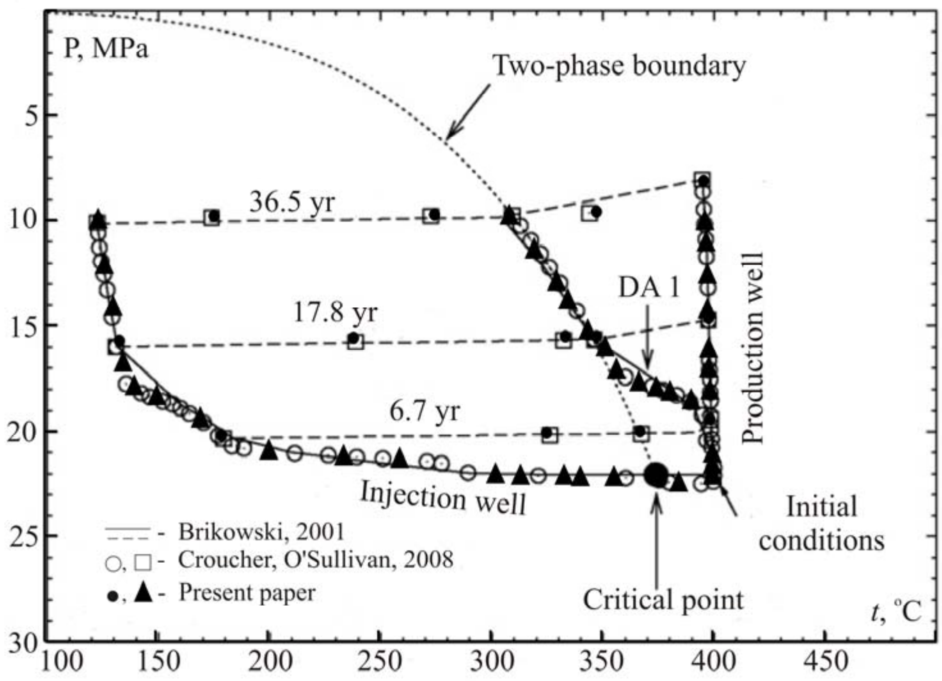

Figure 1. Pressure–temperature diagram for the modelled supercritical five-spot problem. Point DA 1 is at the midpoint between the injection and production wells.

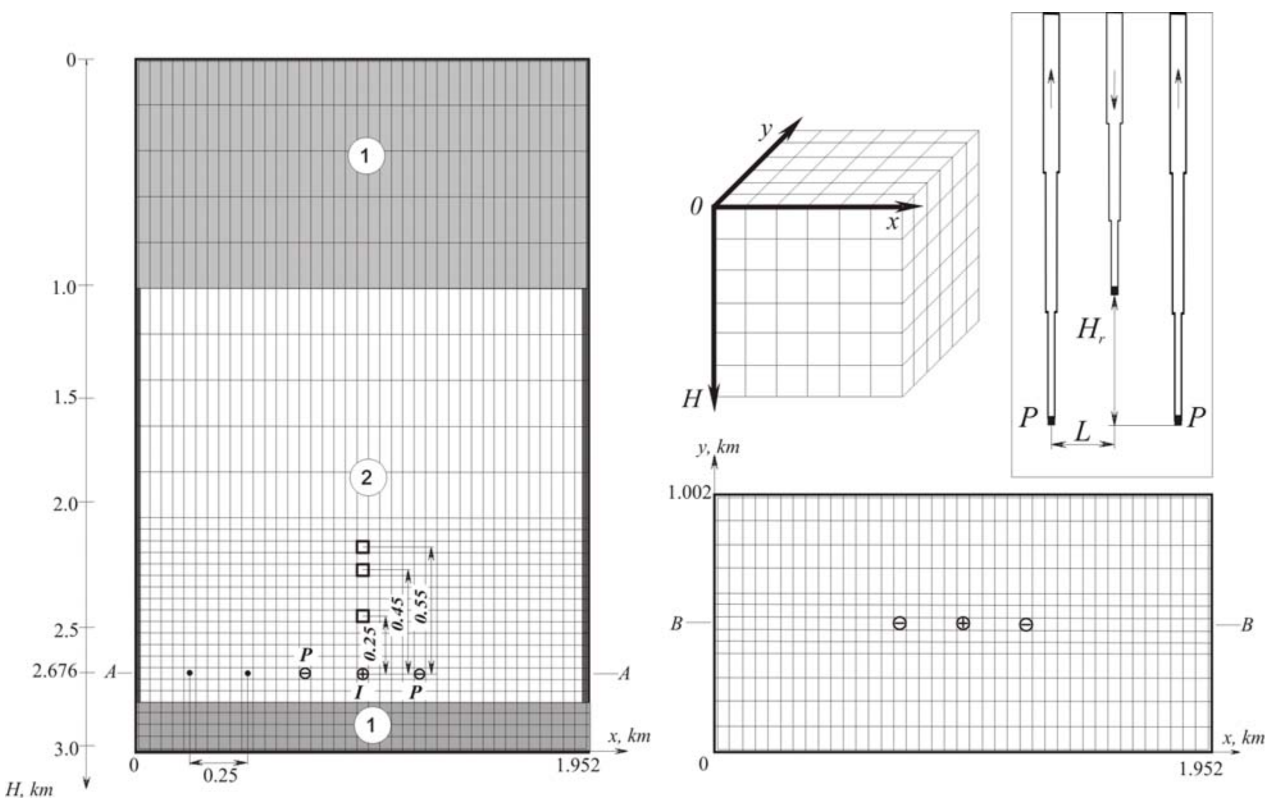

Figure 2. Triplet well pattern with grid. 1 – upper and lower regions of impermeable rocks; 2 – production permeable zone; *P* – producer; *I* – injector.

The injector mass rate is varied from 5 to 15 kg/s. The well depth is 2,700 meters. Value of H_r is varied from 0 to 550 meters, L value is varied from 200 to 500 m. The bottom injection water temperature was assumed to be 100°C. The well open intervals are 50 meters. The dimensions of simulated region are 1,950 – 1,000 – 3,000 meters, Fig. 1. The reservoir consists of one productive zone with rock permeability 10^{-15} m^2 and thickness 1,800 meters and two impermeable rocks (10^{-20} m^2): upper layer with thickness 1,000 meters and lower layer with thickness 200 meters. Initial domain pressure is hydrostatic. On the upper boundary the pressure of 0.1 MPa and temperature of 10^oC are assigned. The initial temperature gradient is $0.137^oC/m$. The initial temperature on the bottom boundary is 420^oC.

It is supposed that productive permeable zone will be created by hydraulic fracturing method. The experience of HDR/EGS creation (Future of Geothermal Energy, 2006) shows possibility to stimulate a large volume of permeable rocks (more than 2 km^3) at depths ranging from 3 to 5 km. Thus the selected geometry of simulated EGS is practically attainable. At the same time there is a possibility of existence of naturally fractured rocks in the above range of depth. For example during the Cooper Basin project drilling the permeable water saturated granites were found out on the depth 4.5 km (Vörös et al., 2007).

SIMULATION RESULTS

The influence of *L* on the circulating fluid parameters

The analysis of phase state changing during exploitation and obtaining of its dependence on geometry well pattern (*L* and H_r) is important for the determination of rational parameters of supercritical EGS. For the case of the wells arrangement "in-line" (H_r = 0 meters) and *L* = 500 meters, in one year after the exploitation beginning as the result of fluid withdrawal and pressure decline a wet steam zone is forming near producer bottoms. The volumetric water saturation increases in a direction from wet steam boundary to producer bottoms (Fig. 3, *a*).

In the other part of productive zone the fluid is supercritical, i.e. *S*=0.5 in terms of HYDROTHERM (Hayba and Ingebritsen, 1994). In two years the condensation front spreads in larger horizontal cross section of the zone. In five years almost whole cross section becomes filled by wet steam. The water saturation grows in direction to producer bottoms. The liquid water zone forms between the producers and injector. In five years steam fraction reduces still more. The ring-like liquid zone forms around the injector. The water pressure is greater than critical one into and around the injector bottom. The superheated steam zone forms below and near producer bottom and spreads during exploitation to boundaries of productive zone. If the distance between producers and injector case is smaller (*L* = 250 and 200 m) the phase transition process has the same character, but its intensity and mean water saturation increase (Fig. 3, *b*). With fixed H_r the distance *L* determines the parameters as follows: 1. a width of disturbed state of productive zone, 2. a rate of rocks cooling, 3. gradients of pressure, temperature and water saturation near-by a region of well bottoms. With smaller *L* the rocks are more cooled and pressure becomes lower near producers bottom and the width of region with considerable water saturation gradient becomes smaller.

The influence of H_r on the circulating fluid parameters

Greater value of H_r gives larger horizontal cross section of productive zone with a wet steam (Fig. 4). In the vertical cross section down to depth of 2,600 meters in a region near the productive zone boundary the fluid exists in a liquid phase (Fig. 4).

Then down to depth of 2,600 meters the water saturation reducing occurs. The fluid exists in a wet steam phase and an almost dry steam (*S*=0.1) exists in a layer with thickness of 200 meters. The layer is continuous along *x* axis when injector bottom is above producer one. In the "in-line" case (H_r=0) the fluid is liquid in a narrow region between injector and producers bottoms. Below the depth of 2.8 km water saturation reduces and wet steam becomes dry and then superheated, and fluid becomes supercritical.

Near by producer the pressure declines and near by injector the pressure raises. The pressure significantly changes only in a productive zone. The decompression front penetrates in the lower impermeable layer in less than 50 meters (Fig. 4).The rocks cooling front spreads in the vicinity of producers and injector bottoms and does not penetrate in lower impermeable layer (Fig. 4). In the rocks between producers and injector the temperature gradient is significantly larger when H_r=0.

When injection rate is 15 kg/s and L=250 meters the well system stably works during 30 years with minimal heat power of 20 MW (Fig. 4).

When H_r=0, *L*=250 m after 20 years of exploitation the full condensation occurs in the producer bottom. With larger H_r (250, 450, 550 m) in the producer bottom the steady pressure and enthalpy decrease and the fluid during the exploitation remains as a wet steam. With growth of H_r from 0 to 550 m a steady value of required injector bottom pressure decreases from 42 to 39 MPa.

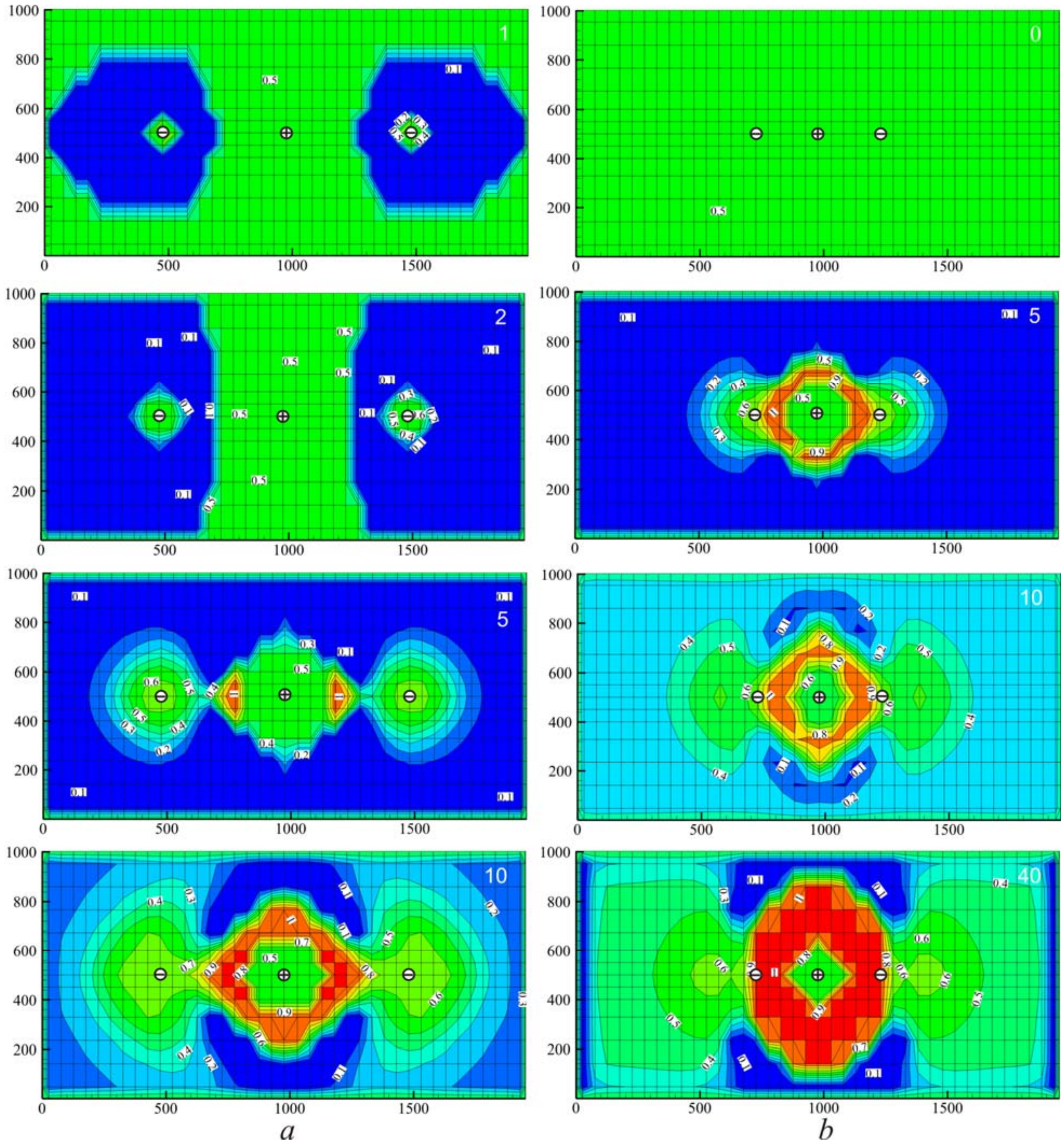

Figure 3. Water volume saturation changing in production zone during exploitation with H_r=0; L = 500 (*a*) and 250 (*b*) meters. The exploitation time (years) is shown in right upper corner.

The influence of injection rate on the system parameters

With the injection rate growth the rate of pressure' and enthalpy' decrease grows too. By the end of exploitation the rate of growth of water saturation on the producer bottom and the rate of growth of required injection pressure grow too (Fig. 5). If the injection rate is 5, 10 and 15 kg/s the steady producer bottom values are accordingly as follows: pressure — 19, 15, 8.5 MPa; temperature — 360, 340, 300 ^{o}C; enthalpy — 1900, 1700, 1400 kJ/kg; mass water saturation — 85, 92, 96 % and the required injection rate is accordingly 26, 34 and 43 MPa.

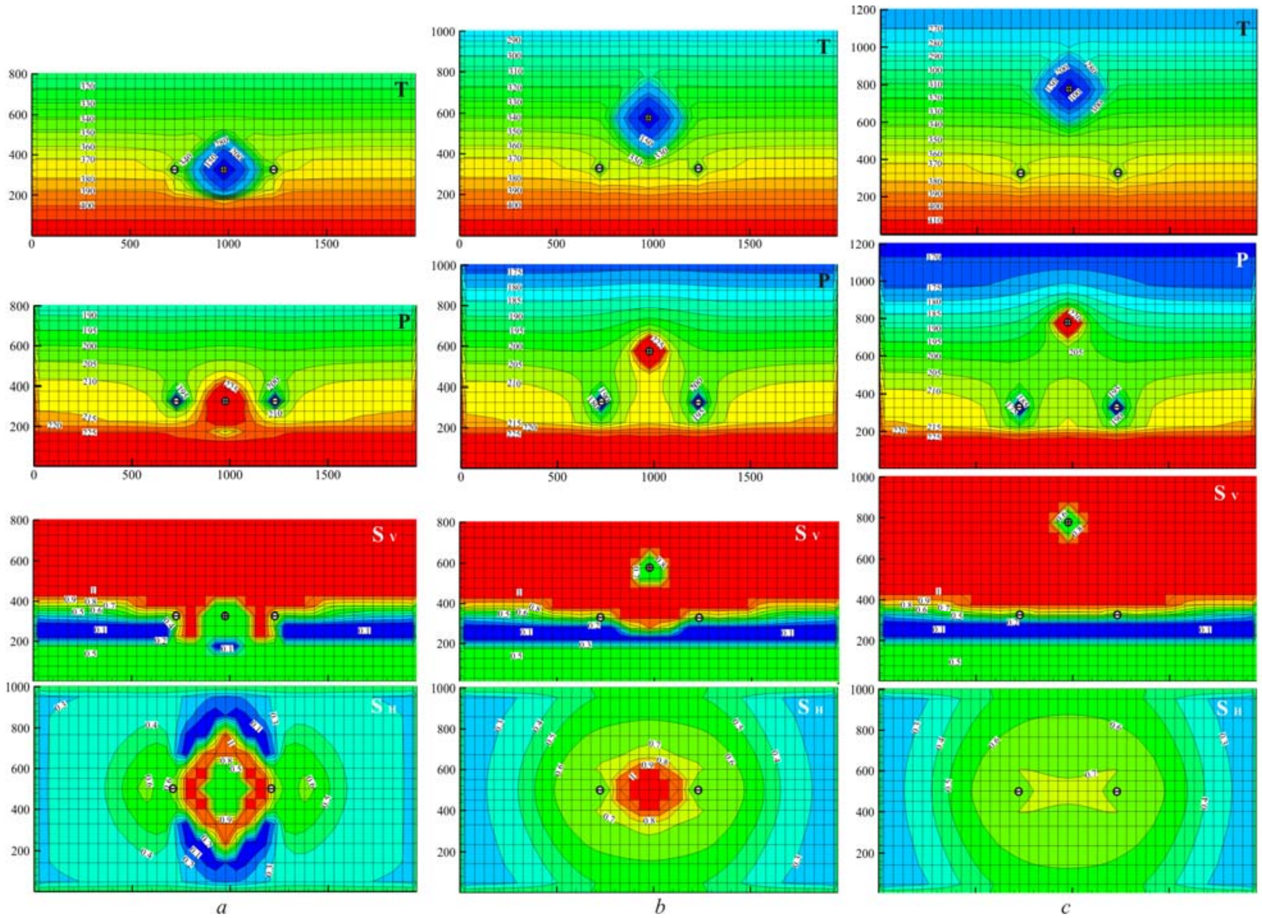

Figure 4. The distribution of production zone parameters after 10 years of exploitation with different H_r (m): *a* – 0; *b* – 250; *c* – 450. T, P, S_V – temperature (^oC), pressure (bar) and water saturation in vertical cross section *B-B*. S_H – water saturation in horizontal cross section *A-A*. Vertical axis is height (m) from model bottom (*H*=3 km), horizontal axis – *x* value (m). For S_H the vertical axis is wide of production zone along *y* axis.

The influence of *L* and H_r on extracted rocks thermal energy

The extracted rocks thermal energy *Q* can be calculated as follows:

$$Q = G\sum_{i=1}^{n}(h_{Pi} - h_{Ii})\Delta t_i \ .$$

Here *G* is the producer rate; h_{Pi}, h_{Ii} are mean fluid enthalpy accordingly producer and injector in the time interval of Δt_i; *n(t)* is a number of calculated time intervals by the end of exploitation time *t*. The enthalpies were calculated on an each time step of simulations.

Case with L=250 m. During five years from the exploitation beginning the extracted heat is almost equal for all values of H_r (Fig. 6). In this initial exploitation period when injector bottom is higher than producer one the extracted heat even larger than its value when H_r = 0. When H_r = 0, in exploitation period less 30 years the mean extracted heat is larger when H_r>0. After 37 years when H_r =250 m the extracted heat is larger when H_r=0 (Fig. 6). After 40 years the difference of extracted heat with different H_r is more 10%.

Case with L=500 m. Here the dependence of extracted heat on H_r is inverse to the above case. When depth of producers and injector is equal (H_r=0) extracted heat is less when H_r>0 (Fig. 6, 7). And for all H_r values the extracted heat is less when *L* = 250 m.

CONCLUSIONS

The well rate, production zone permeability, relative height injector bottom above of the producer bottom, distance between injector and producers influences on technological parameters of supercritical EGS. It more rationally to arrange wells systems with the distance between producers and injector 250 m and H_r=0. Herewith parameters of producers are higher than in the case of *L*=500 m and required injection pressure is lower than with *L*=200 m.

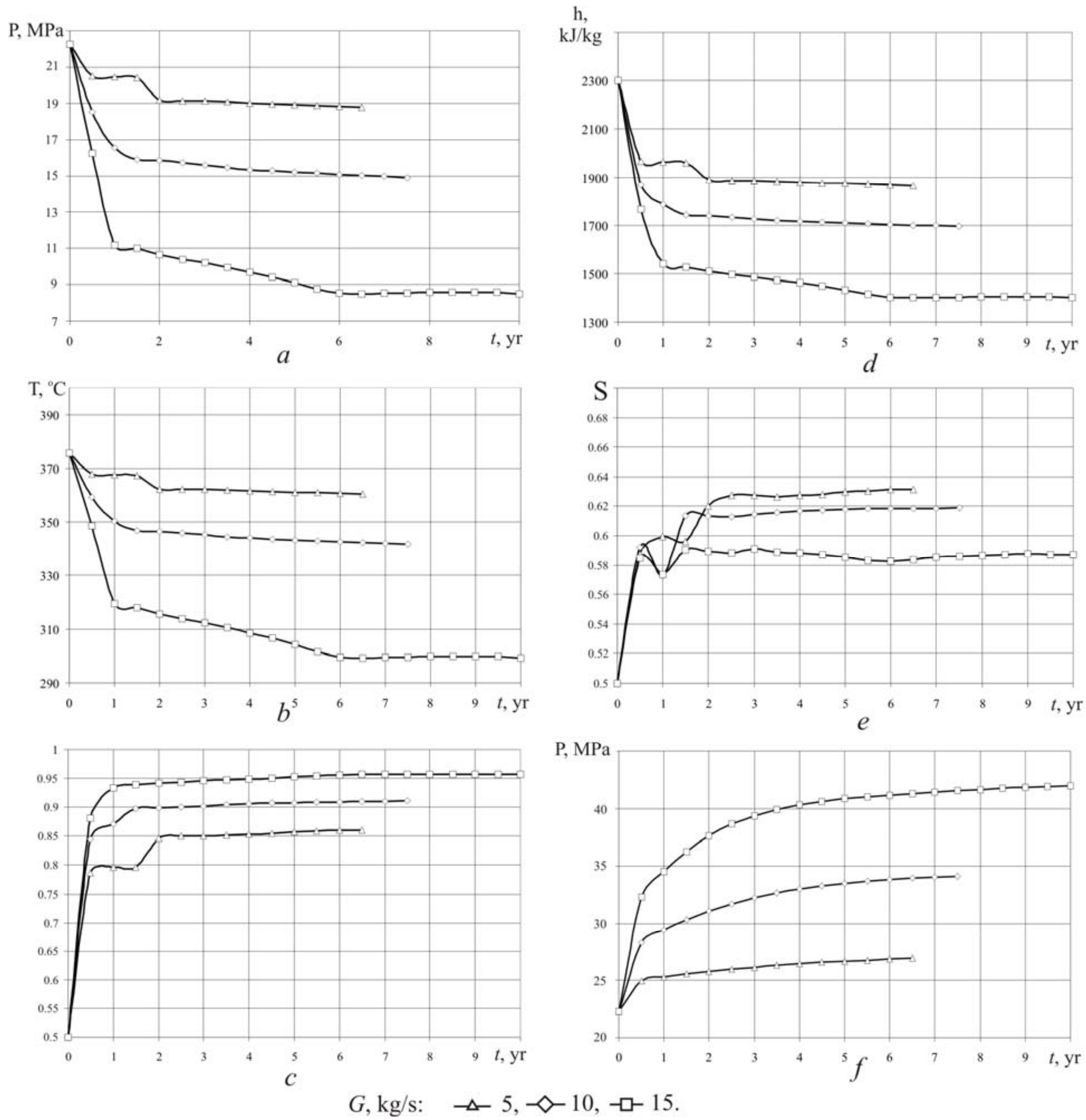

Figure 5. Calculated pressure (*a*), enthalpy (*d*), temperature (*b*), volume and mass water saturation (*c*, *e*), in producer and pressure (*f*) in injector bottom for different injection rate

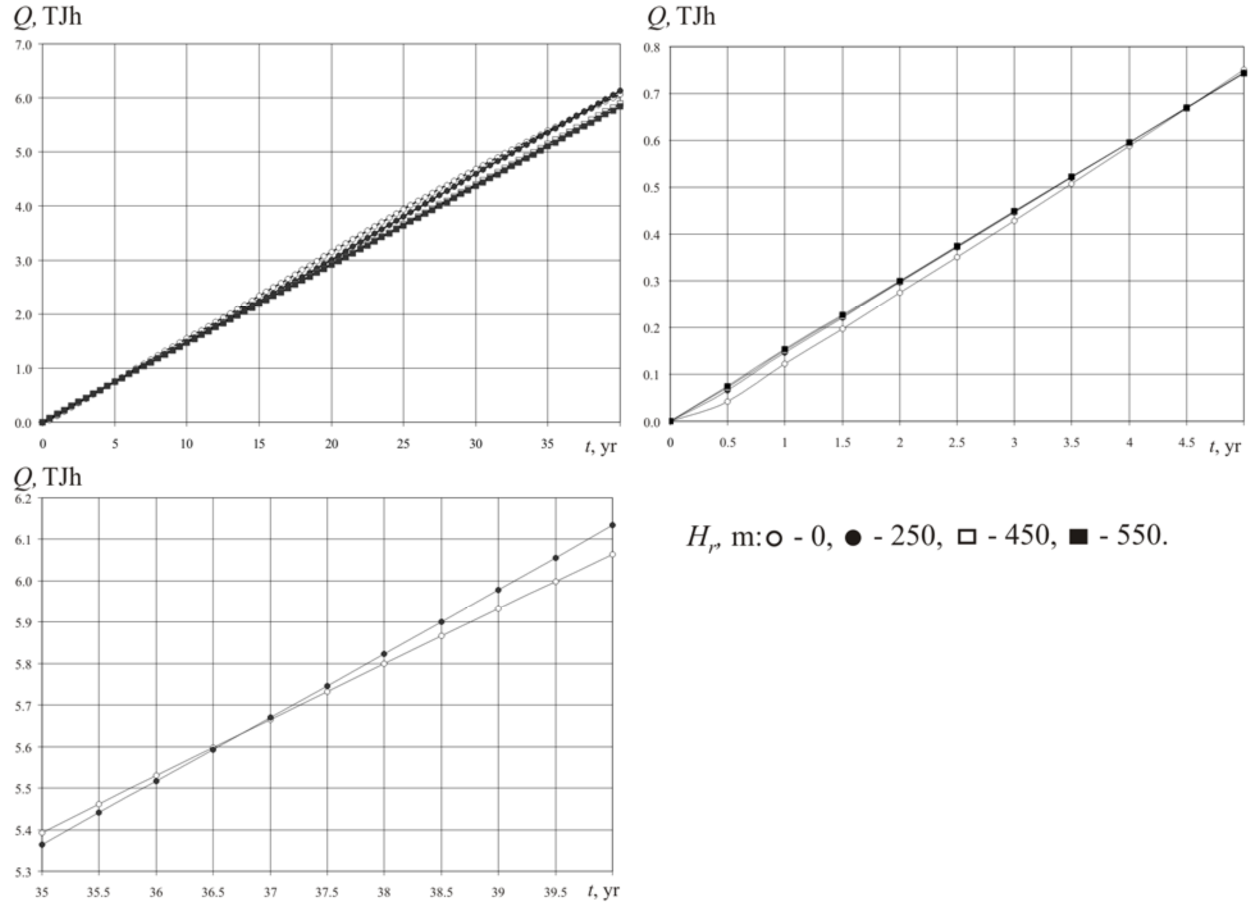

Figure 6. Dependence of extracted thermal energy from production zone rocks during exploitation with L=250 m and different H_r

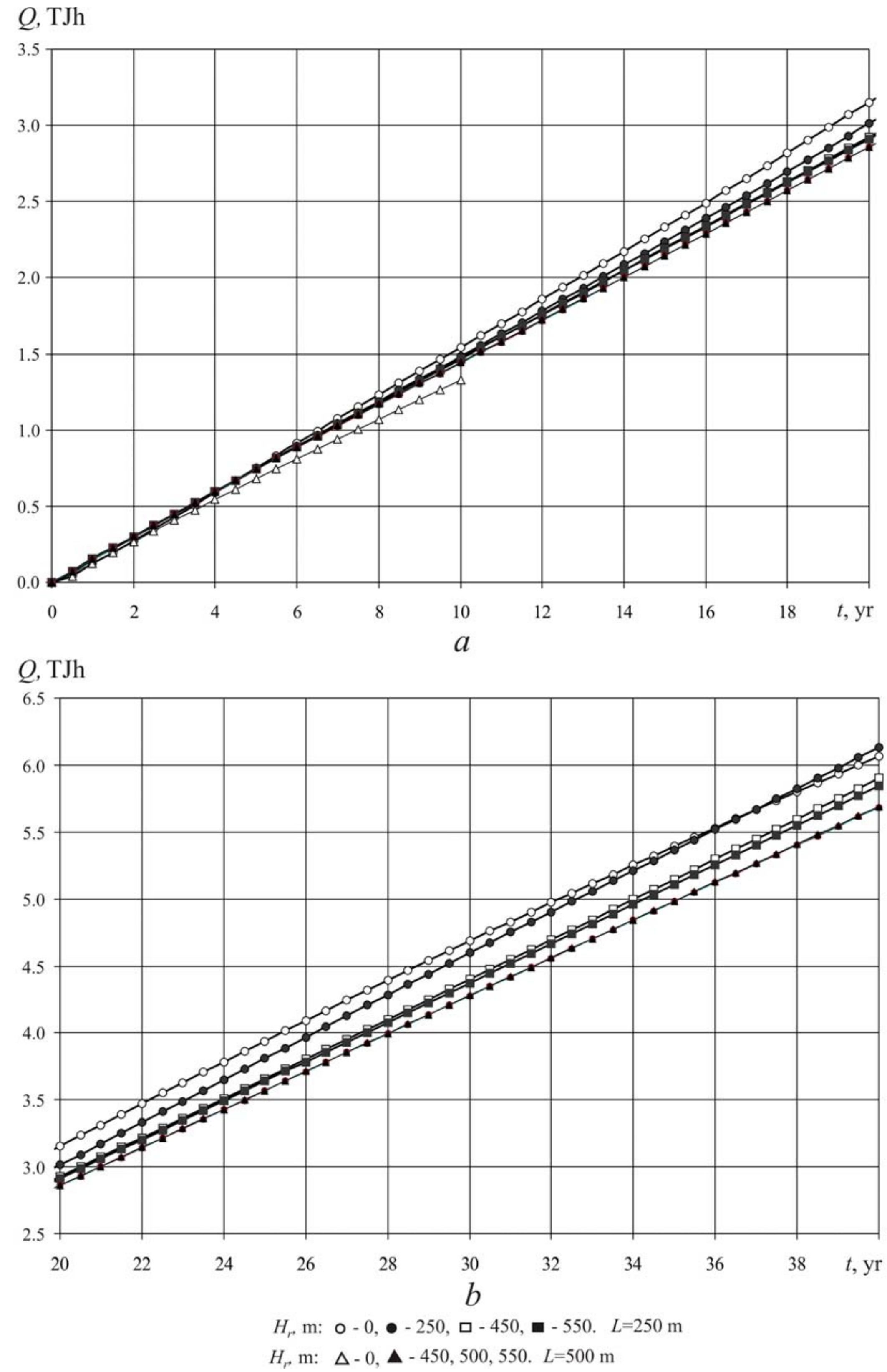

Figure 7. Dependence of extracted thermal energy from production zone rocks during exploitation with different *L* and H_r

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