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Study of EGS Heat Recovery by Multi-Parallel Fracture Model at Desert Peak Field, USA

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ABSTRACT

Heat recovery is an effective way to ensure the long-term stable operation of EGS. Based on the geological background of American Desert Peak field, we studied the heat extraction and heat recovery process with multi-parallel fracture model. The results suggest that, in the initial period of heat recovery process, temperature rises rapidly in a large gradient, while slows down in the latter period. Two main affecting factors of the recovery process are the initial temperature field and the recovery time period. For affecting the initial temperature of the recovery process together, the property of the reservoir (i.e. the stimulation degree of the reservoir and the heat conductivity of the rock) and the fluid flow has the same impact on the heat recovery process as on the heat extraction process. The thickness of heat transfer unit (HTU), fluid flow, and the heat extraction and recovery period are negatively correlated with outlet temperature and lifetime. The heat conductivity of the rock is positively associated with outlet temperature and lifetime. The system with a circulation fluid flow of 100 kg/s, thickness of HTU of 100 m, heat extraction and recovery period of 5 years, has a lifetime of 34.0 years, which is prolonged for 11.9 years compared to continuous heat extraction.

1. INTRODUCTION

Enhanced geothermal system is a system that attempts to extract heat by semi-open circulation through a fractured rock volume, at considerable depth (3~10 kilometers), between injection and production boreholes. The degree of fracturing is enhanced by technical means (man-made fracturing).The objectives of commercial development of enhanced geothermal system (EGS) is to keep a high temperature, and large production rate under the condition that fluid and rock is well contacted in the reservoir, and ensure an enough long reservoir lifetime[Breede et al.(2013); Tester et al. (2006)]. While with the development of EGS project, the temperature of the reservoir is decreased gradually. The heat transfer turns to be slowly when the temperature reduce to a certain range, which always be the temperature of the heat reservoir decrease by 10% or the production temperature decrease by 10%, the geothermal extraction efficiency is low[Axelsson et al.(2005); Sabyal (2012); Sanyal (2005); Vogt et al.(2012); Wu et al.(2015)]. The production should be stopped, the recovery driven by natural forces like pressure and temperature gradients begins. The temperature of the cooling area rise up again to assure a high production efficiency. Studies have shown that the stimulation degree of EGS reservoir has a significant impact on the process of heat extraction. Low stimulation degree will lead to a quick temperature drop during production, and a low reservoir heat extraction rate. The heat stored in the core of the reservoir is difficult to be extracted. Which make it more critical to implement thermal recovery [Mégel and Rybach (2000)].

At present, researches on heat recovery process of low-temperature geothermal has already been well studied. Prichett(1998) studied the evolution characteristics of the pressure, temperature and quantity of steam during the heat extraction and recovery process. Mégel and Rybach (2000) did the numerical simulation study on a low temperature doublet heating system of Basel, France. Results show that shorter production-recovery cycles produce more thermal energy. The time-scale of recovery has been addressed by numerical simulations by Rybach et al.(2000). The recovery times are, for the resource/utilization types considered: high enthalpy, hydrothermal aquifer, and conductive heat extraction by shallow ground-source heat pumps, given which proved the renewability of geothermal energy.

While the thermal recovery of deep geothermal energy has seldom been studied. With the commercialization of geothermal development, the study of heat recovery will become significantly important. At present, Fox et al.(2013) studied the impact of the number of fractures on heat recovery by multi fracture model. Simulation results show that multi-fracture EGS reservoirs have a greater capacity to sustain high outlet temperatures. Chen et al.(2013) studied the impact of heat compensation on EGS heat extraction process. Studies show that the impact of heat compensation effect on production temperature is closely related with the fluid flow field in the heat reservoir, and it is not always improve the EGS production temperature.

In this paper, based on the basic information of Desert Peak geothermal field, we did the heat recovery study with multi-parallel fracture model with surrounding rock. During heat recovery process, cold fluid injection is stopped. Heat recovery of the reservoir is completed with heat conduction. Through the numerical simulation method, we explore the temperature characteristics of fluid and the evaluation of temperature field of rock mass during the heat extraction and recovery process, analyze the impact of different factors (such as, the heat extraction and recovery period, the HTU thickness, the fluid flow, and the heat conduction efficient of rock) on this process, provide references for the establishment of geothermal heat recovery strategy.

2. GEOLOGY BACKGROUND OF DESERT PEAK FIELD

The Desert Peak EGS project is located on the eastern edge of the Desert Peak geothermal field, which is located about 130 km ENE of Reno, Nevada. It is funded by ORMAT Nevada company together with the U.S. department of energy (DOE) which aimed to research on the technical and economic feasibility of building underground artificial heat reservoir and the development of deep geothermal resources with EGS. The ultimate goal of this project is to develop 2~5 MW of EGS-derived power from a stand-alone binary power plant supplied by a well doublet or triplet [Lutz et al.(2003); Robertson-Tait et al.(2005)].

Part detailed geological data on this project have been published[Lutz et al.(2003)]. Because the EGS resource potential around well DP23-1 had been systematically evaluated in 2002~2005 and much geological data had been obtained, this work adopts well DP23-1 data to perform the numerical research. Figure 1 shows the lithology and temperature in DP23-1. The target formation is buried at depth from 1219 m to 2743 m, in which the uppermost layer is in the bottom of the 4th layer: the pT1 Metasediments; and the lowermost layer is in the middle of the 8th layer: the Two-Mica grano-diorite. To simplify the analysis, we neglect the changes of lithology in the target formation and assume the whole target formation is grano-diorite, and its density is evenly distributed and constant The temperature is between 207℃and 216℃, with an average value of 210℃[Lutz et al.(2003); Robertson-Tait et al.(2005); ZENG et al.(2013)].

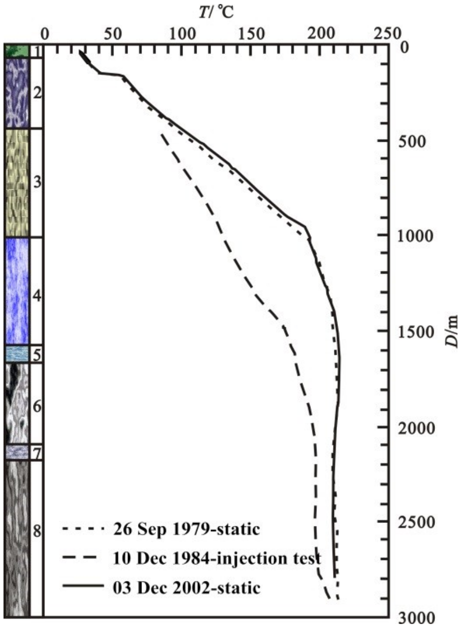

Figure 1: Lithology, completion and downhole survey data, well DP 23-1[Robertson-Tait et al.(2005)]. Formations: 1 – Truckee+Desert Peak; 2 - Chloropagus Formation; 3 - Rhyolite Unit; 4 -pT1 Metasediments; 5 - Quartz Monzodiorite (pT2); 6 - pT2 Metasediments; 7 - Hornblende Diorite (pT2); 8 - Two-Mica Granodiorite

3. MULTI-PARALLEL FRACTURE CONCEPTUAL MODEL WITH SURROUNDING ROCK

EGS reservoir is stimulated fracture system which is only a small part of the hot rock. The stimulated heat reservoir is surrounded by a far more large area of unstimulated zone. In this paper, only the upper and underlying part of hot rock is considered, surrounding rock is introduced to build the multi-parallel fracture model (see Figure 2). We assume that the reservoir is well and uniformly stimulated with an equal fracture width δ. The surrounding rock with the thickness of H is added respectively on the top and bottom of the HTU in numerical simulation. Cold fluid is injected into the fracture system with temperature of T_{f0} and mass flow of Q at the bottom of the injection well. The fluid flows parallel through the fracture averagely, and exchanges heat with the hot dry rock. Heated fluid gathers to the outlet and pumped out through the production well.

Number of fractures in the reservoir：

$$n = \frac{W}{D} + 1 \tag{1}$$

where W,D are the horizontal width of the reservoir, HTU thickness, respectively. Then we can get fluid velocity in each fracture:

$$u_f = \frac{Q}{n\delta W\rho_f} \tag{2}$$

where Q, n, δ, W, ρ_f are the injection fluid flow rate, number of fracture, fracture width, horizontal width of the reservoir, fluid density, respectively.

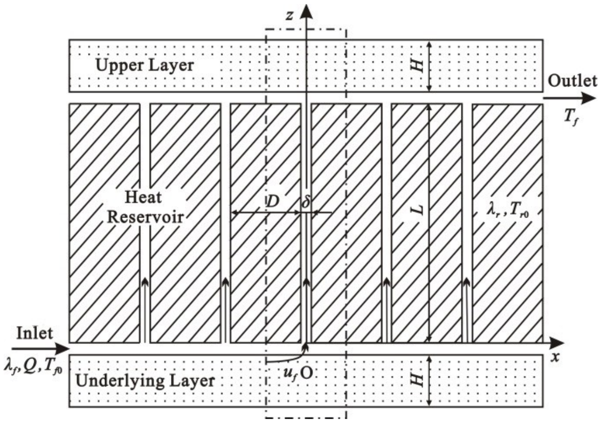

Figure 2: EGS multi-parallel fracture conceptual model with surrounding rock [Sabyal (2012)]. δ and L respectively denote width and length of the fracture, D represents thickness of HTU, H represents thickness of the upper and underlying layer of surrounding rock, T_{r0} represents original temperature of the reservoir and surrounding rock, T_{f0} and u_f respectively represents temperature and velocity of the inlet fluid.

In order to simplify the problem and extract the essence, the following assumptions are made: 1) Rock is homogeneous isotropic permeability blocks, there's no rock fracture fluid output. In low permeability conditions, this assumption can be taken; 2) The heat transfer resistance at the fluid/ rock interface is neglected. This assumption has already been proved to be reasonable in many practical cases[Fox et al.(2013); Ogino et al.(1999)]; 3) The fluid flows in one direction parallel to the fracture with an uniform speed; 4) Heat radiation effect is neglected which is proved to be true by the experiments[TIAN (2009)]; 5) The temperature increase of the fracture fluid is twice of the single side fluid-rock heat transfer effect which is governed by the geological symmetry; 6) The fracture fluid keeps liquid phase during the system running; 7) The thermo-physical properties of both fluid and rock are constant and independent of temperature and position; 8) The fluid flow and heat effect is neglected between the reservoir and the surrounding rock.

In order to evaluate the heat recovery performance, the concept of relative recovery R_c of the reservoir is introduced. The maximum average temperature difference of production and injection $\Delta T_{\max}$ would be reached if the production temperature stayed at its initial value (210ºC). This means that the reservoir has the ability to recover completely the extracted energy. Regarding an operation period of 80 years, one cycle of 40 years production with a subsequent 40 years recovery can be assumed to define the minimum average temperature differences $\Delta T_{\min}$. Relating the temperature difference ΔT of different production schemes to $\Delta T_{\max}$ and $\Delta T_{\min}$ a circulation scheme dependent, relative recovery R_c of the reservoir can be defined as following:

$$R_c = \frac{\Delta T - \Delta T_{\min}}{\Delta T_{\max} - \Delta T_{\min}} \tag{3}$$

4. CALCULATION AND RESULTS

Based on the data of well spacing and reservoir thickness from the Desert Peak EGS field test, the designed target reservoir formation locates at depth from 1219m to 1719 m, with a height of 500 m, horizontal area of 600m×600m, corresponding upper and lower unstimulated layer is set to be 200m thick. We assume that the reservoir is well and uniformly stimulated with an equal fracture width of 10cm [Genter et al.(2007); GUO et al.(2014)]. The initial temperature of the reservoir is 210℃. The injection fluid flow and temperature are 100kg/s and 60℃.

The reliability of the MPFM has been verified. In this work, we used the commercial CFD flow solver, Fluent®. Due to geometrical symmetry (see Figure 2), only half of the basic EGS HTU is simulated (ie. half of the frame selected area in Figure 2). The fracture zone has 1000 grid blocks with 2 in x by 500 in z. For the rock HTU zone, the mesh was discretized in z direction into 1m thick blocks. In order to reduce the number of cells in the grid and speed up the calculation, the mesh has 50 grid blocks in the x direction, with first length of 2.5cm. Totally, there are about 46,000 numerical elements. Grid-independence tests have been conducted to guarantee the present mesh system gives solutions of satisfying accuracy.

Currently we only consider heat transfer and fluid flow. The fluid flow within the fracture is low Reynolds number laminar, single-phase flow. Governing equations that describe the EGS subsurface thermo-hydraulic process thus consist of continuity equation and energy equation. The relative error values of which are respectively 1.0×10^{-3} and 1.0×10^{-6}, and the absolute error value is 1.0. Thermo-physical properties of fluid and rock are assumed temperature-independent, as listed in Table 1[HU et al.(2014); Shaik et al.(2011);].

Table 1. Thermo-physical properties of fluid and rock

	Density /kg·m^{-3}	Heat Capacity /J·kg^{-1}·℃$^{-1}$	Heat Conductivity /W·m^{-1}·℃$^{-1}$	Viscosity /Pa·s
Fluid	900	4200	0.609	0.0003
Rock	2820	1170	2.8	——

4.1 Temperature Field Evolution of Fluid and Heat Reservoir

This part we will apply the model to the simulation study of the heat extraction and recovery process of Desert Peak EGS reservoir. The temperature evolution of the rock HTU during 80 years heat extraction and recovery is presented in Figure 3, where the thickness of HTU is 100m. The rock in the vicinity region surrounding the inlet is first cooled down by the injected cold fluid and a low temperature region forms therein; this low temperature region is seem to gradually triangularly expand outward. The expanding speed of the fluid flow direction is the fastest. After first phase of heat extraction, z direction expands to 440m and -20m, x direction expand to 40m. Heat recovery process carry through on the basis of the temperature distribution of heat extraction. The heat of the unaffected hot zone transfers to the low temperature region which make it shrink in the vertical direction and expand in the horizontal direction. After the first recovery phase, the z direction shrink to -30m~300m with temperature increase, thermal breakthrough exists in x direction. With EGS heat extraction, z direction expands up and down which made the low temperature region get lager and the temperature level decreased. While, heat recovery process carry through after heat extraction and shrink the low temperature region and increase the temperature level.

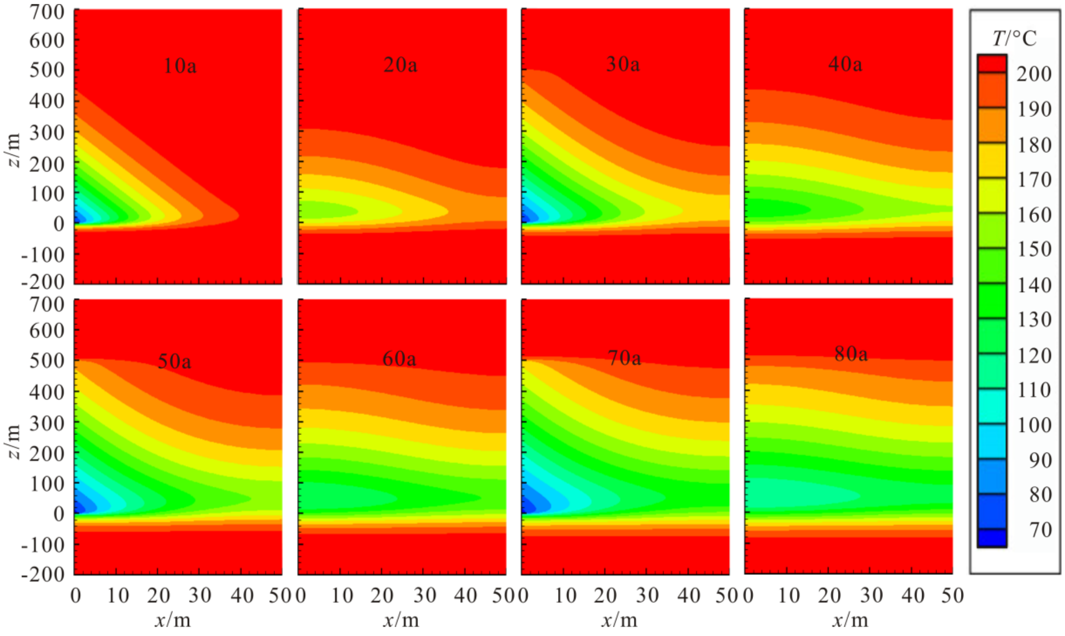

Figure 3: The temperature field evolution of heat reservoir during the process of four phases heat extraction and recovery of Desert Peak field. Time for each phase of heat extraction and recovery period is 10a.

The temperature curve of the rock interface after four phases heat extraction and recovery is presented in Figure 4. It shows clearly that after heat recovery, the temperature level apparently gets higher. Compare to continuous heat extraction, temperature difference with cold fluid gets larger which increased the heat extraction rate. With EGS heat extraction, the temperature level decreased, correspondingly the temperature difference with cold fluid decreased, which weakened the heat extraction and shorted the reservoir lifetime.

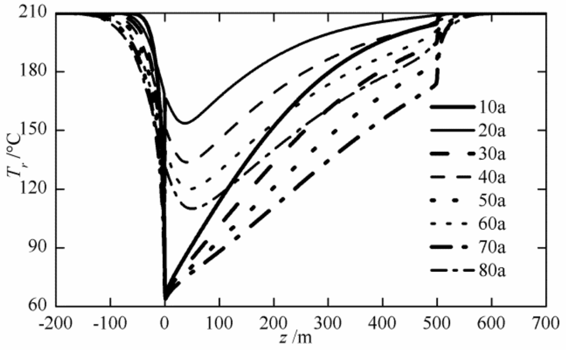

Figure 4: The temperature curve of the rock interface after four phases heat extraction and recovery

The outlet temperature curve during four phases heat extraction and recovery is presented in Figure 5. The outlet temperature increases during heat recovery process. In the initial stage of heat recovery, temperature filed recovers strongly with large temperature gradient owing to big temperature difference. While with operation, temperature difference reduced, and recovery slows down. In the initial stage of heat extraction, the temperature level of heat reservoir keeps high, which results in that the temperature increase in the recovery process is not apparent. While in the second stage of heat recovery process, there exists evident temperature increase. Heat extraction results in large temperature decrease near the fracture zone, large temperature gradient leads to quick and evident temperature increase during heat recovery process.

Compare to the outlet temperature curve of continuous heat extraction, we can easily find that after heat recovery production temperature is much higher and heat extraction efficient gets higher. From Figure 3, after the 3rd stage of heat extraction, the thermal energy in the reservoir is extracted in different degree while with production temperature of 186.2℃. after 10 years heat recovery, the outlet temperature increase to 201.2℃ which can preserve 3 years heat extraction. Take 10% reduction of reservoir temperature as abandon temperature which will be 189℃. Life time of continuous heat extraction is 22.1 years. While run heat extraction and recovery with period of 10 years, the lifetime can prolongs to 31.2 years.

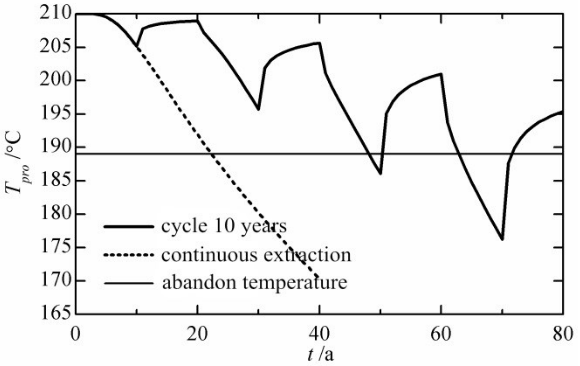

Figure 5: The outlet temperature curve during four phases heat extraction and recovery

4.2 Impact of the Heat Extraction and Recovery Period on Heat Recovery

To guarantee the long term sustainability and renewability of a specific EGS reservoir or field development would require implementing a heat farming strategy. Under this approach, several EGS reservoirs would be used in a rotating manner. When the first reservoir is "depleted" to a point where it is no longer able to satisfy the thermal needs of the surface installation, production would be shifted to a new reservoir. The process would continue until the first reservoir has recovered sufficiently to be restarted or re-stimulated[Fox et al.(2013)].

For a given reservoir model the circulation scheme leads to a specific production temperature development. For the 100 m spaced fracture zone network model the production temperature of a constant circulation rate of 100kg/s and production-recovery cycles of 5, 10, 20 and 40 years have been calculated (Figure 6). A comparison of the production temperature shows that the temperature will remain on a level, which is the higher the shorter the production-recovery cycle period is. In the latter period of heat extraction process, the outlet temperature turns to be stable especially when the production-recovery cycle period is long. This is because of heat conduction in the vertical direction, that is to say, heat recovery reaches a stable state that heat transferred to low temperature zone equals to the heat conducted from the high temperature zone. Long term heat recovery will results in heat conduction from high temperature zone to cold zone. The temperature of high temperature zone will decrease which is not beneficial to long term efficient heat extraction.

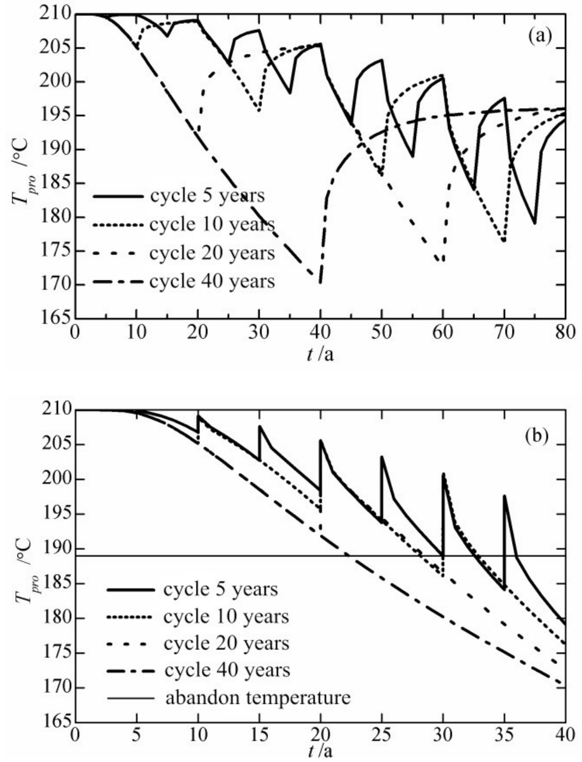

Figure 6: Impact of the heat extraction and recovery period on the outlet temperature: (a) heat extraction and recovery process; (b) for convenience of data analysis, heat recovery data is eliminated, and left heat extraction process only.

For the considered circulation schemes the maximum value for the relative recovery R_c of 39.4 % is obtained with a production-recovery-cycle of 5 years (Table 2). Correspondingly, the longest reservoir lifetime is 34.0 years which is 11.9 years longer than continuous heat extraction.

Table 2 Impacts of the heat extraction and recovery period on the recovery of the reservoir

Circulation scheme	Circulation rate Q /kg·s^{-1}	Considered time period /a	Average temperature difference ΔT /℃	Energy production /%	Reservoir recovery R_c /%	Lifetime /a
1×40 a（no thermal drawdown）	100	80	150.00	113.74	100.00	——
8×5 a	100	80	139.02	105.41	39.40	34.0
4×10 a	100	80	137.46	104.23	30.77	31.2
2×20 a	100	80	135.10	102.44	17.75	28.6
1×40 a	100	80	131.88	100.00	0.00	22.1

4.3 Impact of the HTU Thickness on Heat Recovery

Research has shown that the HTU thickness has significant influence on heat extraction process. In constant flow reservoir, HTU thickness is negatively correlated with production temperature and heat extraction efficient. The production temperature of a constant production-recovery cycles of 10 years and HTU thickness of 40, 100 and 200m have been simulated (Figure 7), where the dashed lines are the production temperatures of relative cases under continuous heat extraction situation. With the increase of HTU thickness, the production temperature decreases, the reservoir lifetime shortened, but the temperature increase is evident.

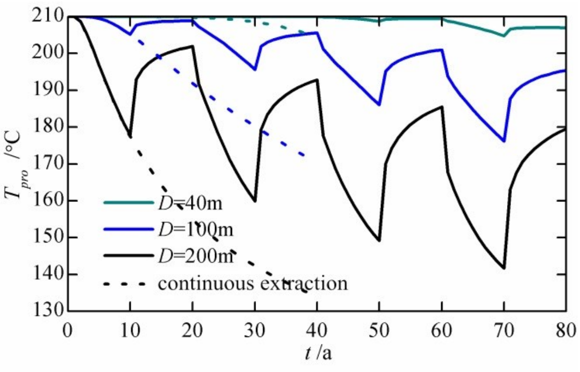

Figure 7: Impact of the HTU thickness on the outlet temperature

After 20 years heat extraction, temperature distribution of the rock HTU is shown in Figure 8, the upper layer is 20 years continuous heat extraction; the under layer is 2 production-recovery cycles. After comparison we can see that after heat recovery the cooling zone tends to be shrink in the vertical direction and expand in the horizontal direction. The total temperature level is increased. Combined with Figure 7, when the thickness is 200m, the temperature recovery gradient is the largest, the outlet temperature can increase by 38.7 ℃. While the temperature of the vicinity region surrounding the fracture is still low and can not maintain long-term high temperature production. This is because the stimulation degree of the reservoir is low, the fluid flow rate is large in each fracture. The temperature decrease of the near fracture region is quickly which make it difficult to extract the heat stored in the core of the rock HTU. When the reservoir is well stimulated, the flow rate of each fracture is small, the heat is fully exchanged between the fluid and rock which can the production temperature keep a high level for a long time.

Besides, from Figure 8 we can notice that when the HTU thickness is small, after same time of operation, the under layer of surrounding rock can be extracted in a larger extent. The surrounding rock is unstimulated high temperature rock without inner connected fracture networks. The permeability is low and is difficult to be explored. The under lying surrounding rock can be well extracted by the cold fluid with low velocity when the reservoir is well stimulated.

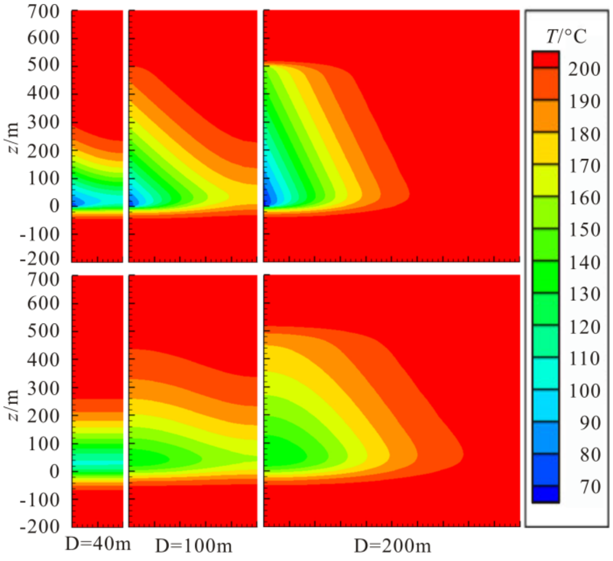

Figure 8: Comparison of temperature distribution in the rock HTU after 20 years continuous heat extraction and two stages of heat extraction-recovery process

For the considered HTU thickness the maximum value for the relative recovery R_c of 30.77 % is obtained with a HTU thickness of 100m (Table 3). When the HTU thickness is 40m, the production temperature maintains a high level with small temperature gradient and weak recovery effect. When the HTU thickness is 200m, the temperature level of the near fracture zone is low. Although the temperature increasement of the recovery process is high, the heat stored in the core of the rock is still difficult to transferred to the fracture interface. Therefore, the production temperature decreases quickly. Correspondingly, the reservoir lifetime with recovery is 8.8 years which is only 2 years longer than continuous heat extraction.

Table3 Impact of HTU thickness on the recovery of the reservoir

HTU thickness	Circulation scheme	Average temperature difference ΔT/℃	Reservoir recovery R_c /%	Lifetime /a
40 m	1×40 a	149.09	4.63	——
	4×10 a	149.13		
100 m	1×40 a	131.88	30.77	22.1
	4×10 a	137.46		31.2
200 m	1×40 a	101.76	20.34	6.8
	4×10 a	111.57		8.8

4.4 Impact of Fluid Flow on Heat Recovery

EGS extracted heat through injecting cold fluid into the reservoir. The flow rate of the reservoir is not only related to the heat extraction rate, but also results in the temperature distribution of the reservoir. The production temperature of a constant production-recovery cycles of 10 years and flow rate of 50, 100, 150 and 200kg/s have been simulated (Figure 9), where the dashed lines are the production temperatures of relative cases under continuous heat extraction situation. With the increase of flow rate, the production temperature decreases, the reservoir lifetime shortened. Although the temperature increase is evident, the total temperature level is still low. While small flow rate can maintain a sustainable high efficiency heat extraction with small temperature decrease.

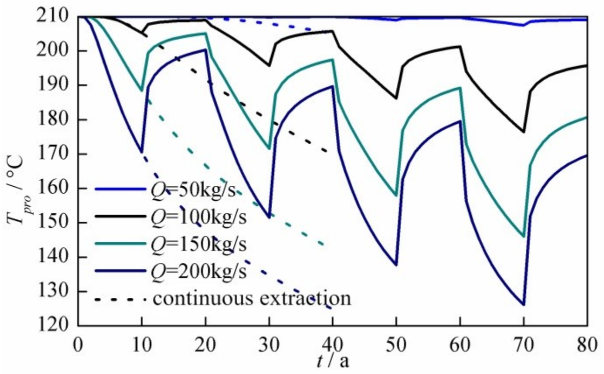

Figure 9: Impact of fluid flow on the outlet temperature

For the considered flow rate the maximum value for the relative recovery R_c of 58.47 % is obtained with a flow rate of 50kg/s (Table 4). Smaller flow rate relate to higher relative recovery and longer lifetime after heat recovery. When the flow rate is 50kg/s, the production temperature maintains a high level. After heat recovery, the production temperature can basically maintain the initial temperature of the reservoir. The relative recovery R_c is high which is because both the continuous heat production temperature ΔT_{min} and the production temperature with heat recovery ΔT is maintain in a high level with a relation of $\Delta T \approx \Delta T_{max}$. When the flow rate is 200kg/s, compared to continuous heat extraction, the average production temperature increased a lot but still far more lower than ΔT_{max}. Therefore, relative recovery is low. Correspondingly, the reservoir lifetime can not be effectively prolonged by heat recovery.

Table4 Impact of fluid flow on the recovery of the reservoir

Circulation rate	Circulation scheme	Average temperature difference ΔT/℃	Reservoir recovery R_c /%	Lifetime /a
50kg/s	1×40 a	148.82	58.47	——
	4×10 a	149.51		
100kg/s	1×40 a	131.88	30.77	22.1
	4×10 a	137.46		31.2

150kg/s	1×40 a	111.49	19.71	9.8
	4×10 a	119.08		13.7
200kg/s	1×40 a	95.36	13.93	5.5
	4×10 a	102.97		6.5

4.5 Impact of Heat Conductivity of Rock on Heat Recovery

The stimulation degree of the reservoir is limited, the contact area of fluid and rock is limited, therefore the heat conduction speed exerts a tremendous influence on heat extraction efficiency and temperature distribution. The production temperature of a constant production-recovery cycles of 10 years and the rock heat conductivity of 2.4, 2.8 and 3.5 W/(m·K) [Fox et al.(2013); Li et al.(2015); Mégel and Rybach(2000); Wu et al.(2015)] have been simulated (Figure 10), where the dashed lines are the production temperatures of relative cases under continuous heat extraction situation.

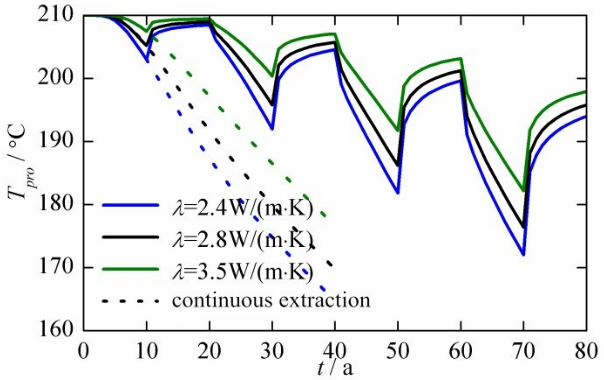

Figure 10: Impact of heat conductivity of rock on the outlet temperature

With the increase of heat conductivity, the production temperature increases, the reservoir lifetime prolonged. This is because high heat conductivity increases the heat transfer speed which enhanced the heat exchange rate between fluid and rock interface. The decrease rate of T_{pro} is lowered. The average production temperature is increased and the lifetime is prolonged. For the considered heat conductivity the relative recovery R_c is almost the same (Table 5). The lifetime is prolonged in the same effect with about 8~9 years. Therefore, for conduction heat reservoir type, larger heat conductivity relates to higher production temperature, longer reservoir lifetime, more suitable for commercial development.

Table5 Impact of heat conductivity of rock on the recovery of the reservoir

λ_r	Circulation scheme	Average temperature difference ΔT /℃	Reservoir recovery R_c /%	Lifetime /a
2.4W/(m·K)	1×40 a	128.39	30.03	18.9
	4×10 a	134.88		27.7
2.8W/(m·K)	1×40 a	131.88	30.77	22.1
	4×10 a	137.46		31.2
3.5W/(m·K)	1×40 a	136.27	31.54	27.6
	4×10 a	140.60		35.6

5. DISCUSSION

Heat recovery process is mainly controlled by heat conduction effect. According to Fourier law of thermal conduction, the local heat flux density is equal to the product of thermal conductivity, and the negative local temperature gradient. The heat flux density is the amount of energy that flows through a unit area per unit time. The thermal conductivity is often treated as a constant, the temperature distribution after heat recovery is determined by the temperature filed after heat extraction and the heat recovery period.

In the above, the influence of heat extraction and recovery period, HTU thickness, fluid flow and rock heat conductivity on heat recovery. Compared to previous studies, it is easy to find out that the HTU thickness, fluid flow and rock heat conductivity have same affections on heat extraction and heat recovery. The affecting factors of heat extraction result in the temperature field (the initial temperature filed of heat recovery). Heat recovery process goes through on the basis of heat extraction to recovery the temperature field of heat extraction. Therefore, the affecting factors of the heat extraction have the same impact on heat recovery. Short heat extraction and recovery period is advantageous to efficient heat extraction. Temperature increases quickly in the initial stage of recovery process and slows down in the latter period. Short recovery period can protect the recovery process stay in the efficient recovery zone by reducing heat conduction in the vertical direction. The high temperature zone can maintain a relative high temperature which can ensure that the fluid can be heated up to a high production temperature. Correspondingly, the reservoir lifetime can be prolonged.

Multi-parallel fracture model with surrounding rock can be used to simulate the temperature evaluation of fluid and reservoir during heat extraction and recovery process, analyze the main affecting factors of heat recovery. While the model is still exist deficiencies. First, the temperature of the reservoir increases with the deepen of stratum owing to temperature gradient. Different layer of reservoir have different impact on heat recovery which made the consideration of temperature gradient more important. Second, temperature of the reservoir decreases with heat extraction which will make the rock shrink and the fracture widened, then the flow resistance decreases. On the contrary, the temperature of the cooling zone will recovery during the heat recovery process which make the rock expand and the fracture get narrow again, and the flow resistance increased. The change of flow resistance will not only affect the heat extraction performance, but also affect the pump power consumption and economical efficiency of heat extraction for constant flow fields. Therefore, the volume expansion effect of heat reservoir caused by temperature change should be considered. By experimental method we can qualify this effect and revise the results.

6. CONCLUSION

The reservoir temperature and production temperature decreases with EGS heat extraction. In order to ensure the long-term stability of the EGS efficient heat extraction, the study of reservoir thermal recovery process is of great significance. Based on the geological background of American Desert Peak field, we studied the heat extraction and heat recovery process with multi-parallel fracture model. The results suggest that, heat recovery can effectively restrain the temperature decrease caused by heat extraction and ensure the long-term stable operation of EGS. In the initial period of heat recovery process, temperature rises rapidly in a large gradient, while slows down in the latter period. Two main affecting factors of the recovery process are the initial temperature field and the recovery time period. For affecting the initial temperature of the recovery process together, the property of the reservoir (i.e. the stimulation degree of the reservoir and the heat conductivity of the rock) and the fluid flow has the same impact on the heat recovery process as on the heat extraction process. The thickness of heat transfer unit (HTU), fluid flow, and the heat extraction and recovery period are negatively correlated with outlet temperature and lifetime. The heat conductivity of the rock is positively associated with outlet temperature and lifetime. The system with a circulation fluid flow of 100 kg/s, thickness of HTU of 100 m, heat extraction and recovery period of 10 years, has a lifetime of 31.2 years. With a heat extraction and recovery period of 5 years, the lifetime will be 34.0 years, which is prolonged for 11.9 years compared to continuous heat extraction.

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