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A Novel Geothermal System for Winter Heating Application in Severe Cold Regions

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Abstract: In this work, a novel enhanced geothermal combined heat pump system (MLEGHP) is proposed for winter heating in severe cold regions. Taking Shenyang city as an example, we technologically investigate the applicability of this novel MLEGHP system in the heating-dominated regions over a 30-year period. Based on the real geological data, the hydraulic fracturing simulation and reservoir simulation are conducted successively. The results indicate that the MLEGHP system can continuously work efficiently without performance deterioration and strengthening the heating reliability during long-term operation in cold regions.

Keywords: *enhanced geothermal system (EGS), hydraulic fracturing, reservoir simulation, heat pump*

1. Introduction

Energy consumption for heating and domestic hot water is very high in severely cold regions. In urban areas of north China, heating accounted for up to 23% of the total building energy consumption in 2008 [1]. Over 80% of ground source heat pump (GSHP) projects are located in North or Northeast China [2]. In these regions, the heating load of a building is dominant. However, the heat extracted from underground is far less than the amount of injection, which causes the heat source temperature gradually declining year by year [3]. This problem could lead to degradation in the GSHP's heating performance, even resulting in failure of the GSHP system after several years [4].

A number of solutions have been proposed for maintain the ground thermal balance in cold regions. These solutions include (1) increasing the number of boreholes or the space between boreholes; (2) integrating an auxiliary energy into GSHP to create a hybrid GSHP system and (3) using seasonal thermal storage during the non-heating season. The solution (1) cannot fundamentally solve the thermal imbalance problem and increases the drilling cost and land occupation. The auxiliary energy of solution (2) mainly includes solar [5-7] and fossil fuel [8]. However, the investment in the thermal solar collector is high and there is no enough space to arrange large-area solar collector in high-density city of China. For the solution (3), the thermal energy which was stored into ground during non-heating period mainly comes from ambient air and solar radiation. This method was studied theoretically and experimentally in recent years and the hybrid GSHP systems integrated with solar energy storage are especially popular at present [9]. However, the reliability of solar energy and ambient air energy are seriously affected by the weather and the problems of adopting solar collector aforementioned still exist.

Remarkably, little work was devoted to the study on the extraction of deeper geothermal energy resources and on the performance improvement of ground heat exchanger (GHE). Research suggests that the main factors influencing heat pump performance and heat output is the temperature of outlet water from GHE, which mainly depended on injection water temperature, ground source temperature and GHE performance. Thus, in order to fundamentally improve the heat pump performance and heat production capacity, we should focus on two aspects: selecting a heat source with a higher temperature and improving the GHE performance. In this work, we defined the system which meets the above two aspects and combines heat pump as medium-low temperature enhanced geothermal heat pump (MLEGHP) system.
The purpose of this work is to technologically investigate the applicability of this novel MLEGHP system in the heating-dominated regions over a 30-year period. Taking Shenyang city as an example, the target formation was selected and artificially stimulated based on the real geological data. Furthermore, the hydro-thermal characteristics of the medium-low temperature EGS based on the stimulated results are investigated in detail. This integrated approach gives insight into whether or not the MLEGHP system is suitable for winter heating in cold regions.

2 Methodology

We first parameterized the geological model based on the available data and new laboratory experiments. Then, we simulated hydraulic fracturing treatments in the potential target formation to evaluate what fracture dimension can be achieved by one single treatment. Subsequently, the hydraulic and thermal performances of the stimulated reservoirs were simulated for a lifetime of 30 years. In the end, through dynamic simulations, the outlet water temperature of the production well and output heat under long-term operation can be obtained and can be used to analyze the system energy efficiency.

2.1 Description of the MLEGHP:

The brief schematic diagram of the proposed MLEGHP system is illustrated in Fig.1. The system mainly consists of four parts: underground EGS heat exchanger system, surface plate heat exchanger group, heat pump system and terminal heating system.

For the EGS part, it includes the following sections: injection well, artificial thermal reservoir (fractures/ fracture networks) and production well. A 3-horizontal well EGS is proposed with one injection well flanked by two production wells drilled parallel to the minimum horizontal stress.

The plate heat exchanger group, heat pump system and terminal heating system are chosen according to the EGS capacity and building types, respectively. It should be noted that the outlet water temperature of EGS can be very high, thus the heating performance of heat pump system will be relatively high. In this study, the system is designed to run only in heating period.

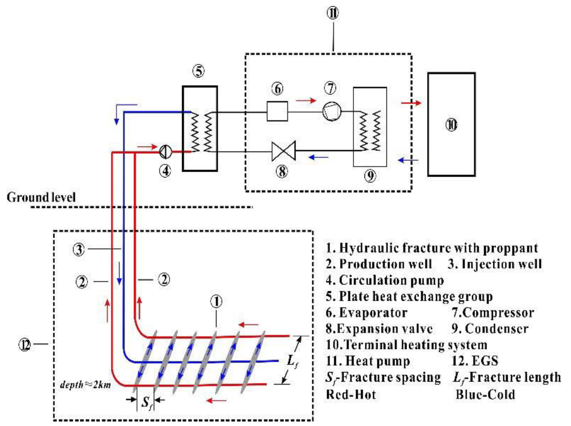

***Fig.1** The schematic map of MLEGHP system*

2.2 Geological background in Shenyang city:

Shenyang city is located in the eastern Liaohe basin in China which possesses a large oil deposit. In this case we adopt the deep well Ou45 located in eastern Liaohe basin as the study well. The logging data interpreting result of well Ou45 in the range of 2000-3500m is illustrated in Fig.2. It can be seen that in this interval the main stratum is the sha_3 member (Es3) with a thickness over 1500m, and there are two main lithology of sedimentary intercalation and thick-layer volcanic. The sedimentary intercalation mainly lies in the range of 2000-2400m with a low density, permeability (avg. 1mD) and porosity (avg. 0.1). Meanwhile, the basic basalt has a low permeability of avg. 0.1mD and low porosity of avg. 0.01. In summary, for the formation of 2000-3500m in Ou45 permeability is too low (<1 mD) to produce hot water economically. Thus the permeability of the Es3 formation in the eastern Liaohe basin needs to be enhanced artificially to develop the geothermal potential in this region.

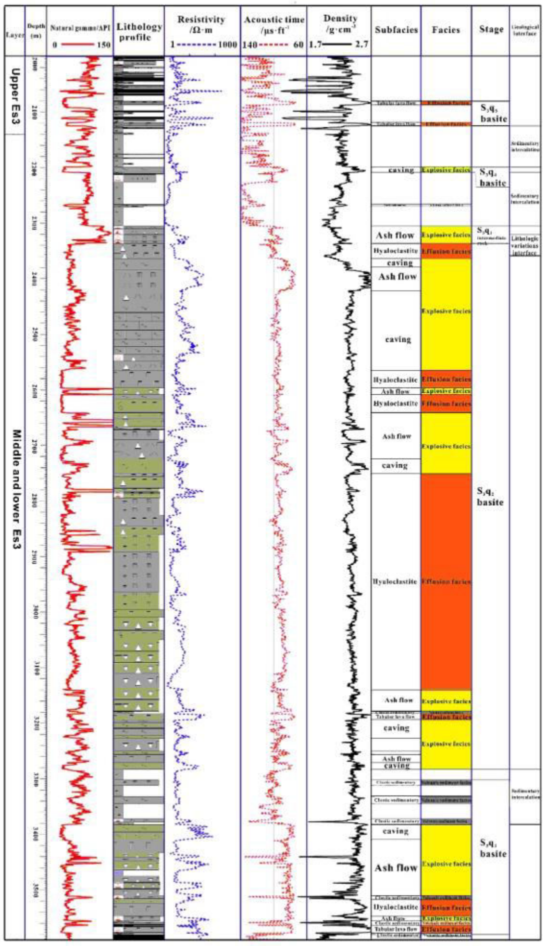

***Fig.2.** Logging results of well Ou45 in 2000-3500m.*

2.3 Hydraulic fracturing simulations:

In this study we focus on the application of conventional gel-proppant treatments. It can be concluded from the logging interpret results (Fig.2) that the sedimentary intercalation of 2000-2500m is suitable as the target formation because of a much softer rock and lower stress.

Fracturing simulations in this work were conducted by using STIMPLAN software, which is developed by K.G. Nolte and Mike Smith, and is widely used for fracturing design in the oil and gas industry.

The 3D fracturing model was established between 2000m and 2500m based on the reservoir properties previously mentioned. In this model, perforated interval is set in 2220-2400m, fractures initiate and develop in tensile mode only. Calculations are based on mass conservation, momentum conservation, continuity and a width-opening pressure equation.

All reservoir parameters come from logging data of well Ou45.

2.4 Thermal-hydraulic reservoir simulation:

The above created fracture properties were taken as input parameters into the 3D coupled thermo-hydraulic reservoir model. We assume that the formation is homogeneous and isotropic in the same depth.

The lifetime of MLEGHP is set to 30 years. We assume that MLEGHP system runs 24h continuously in heating mode (Nov.1-Apr.1, 5months), and stops to recover heat from wall rock in non-heating season (Apr.1-Nov.1, 7months).

In this numerical study, we used the TOUGH2-EOS1 code, which has been developed at Lawrence Berkeley National Laboratory. For subsurface water flow, the EOS1 module provides a useful simulation.
In this study, all boundaries are assumed to be no-flow for mass and heat transfer. The slight boundary effect can be ignored due to the large volume of the model in Y direction. Main parameters used in simulations are shown in Table 1.

***Table 1:** Reservoir parameters for hydro-thermal simulation*

Parameter	Value
Rock density	2500kg/m³
Rock porosity	0.1
Rock permeability	1mD
Rock thermal conductivity	2.7W/(m·K)
Rock specific heat	806 J/(kg·K)
Fracture density	2082 kg/m³
Fracture porosity	4%
Fracture permeability	257D
Fracture thermal conductivity	2.7 W/(m·K)
Fracture specific heat	806 J/(kg·K)
Initial pressure	P=23.50-0.01Z (MPa)
Initial temperature	69°C
Productivity index	$5.5\times10^{-12}m^3$
Production flow pressure	23.50MPa

3 Results and discussions:

3.1 Hydraulic fracturing results and discussions:

The fracturing simulation results are shown in Fig.3. It can be seen that the fracture was restricted in the formation of 2200-2400m. The fracture half-length was 432m, height was 200m and width decreased from 0.350 to 0 cm from injection point to fracture edge. The fracture conductivity decreased also from 900 to 0 mD•m accordingly. Thus the average fracture permeability is calculated as 257D. The heat exchange area was 172,960 m^2. The total injected fracturing fluid and proppant are 20,000 m^{3}and 317.6t, respectively.

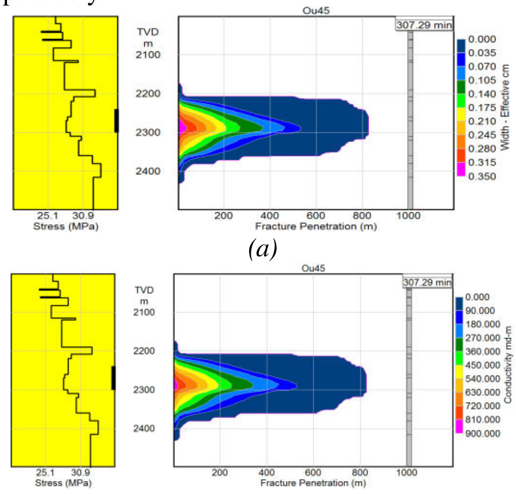

***Fig.3.**Hydraulic fracturing simulation results: geometry (a) and conductivity (b).*

3.2 Hydro-thermal simulation results and discussions:

3.2.1 Production water temperature

Fig.4 shows the evolution of production water temperature T_{pro} when injection flow rate q_{inj} is 2kg/s during the 30 year production period. The whole production process can be divided into two stages: a stable production stage and a declining stage. In the first stable stage, T_{pro} maintains at initial reservoir temperature of 69°C since the production begins, and this stage lasts for the first 2 years. However, in the second stage from the 2th year, T_{pro} gradually declines from 69°C until to the final 63.8°C, about dropping by 7.5%, and corresponding reservoir temperature near the production well decreases from 69°C to final 65.4°C, dropping by 5.2%. However, the production water temperature is still very high after 30 year operation which could continuously support a good performance of surface heat pump system. Therefore, from the view of outlet water temperature, the proposed system performs very well.

3.2.2 Heat production power

Fig.5 shows the evolution of heat production W_h during the 30 year production. The results show that the W_h just slightly declines from 0.53MW to final 0.50MW in the whole production process. So during the whole life of the MLEGHP system, heat production keeps almost at constant and the thermal energy is steadily extracted out. Therefore, this proposed system will last much longer than 30 years with a very stable performance simultaneously.

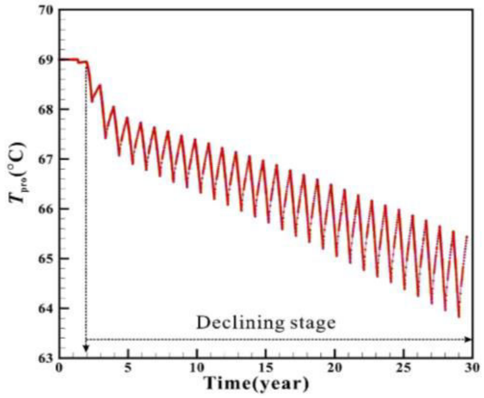

Fig.4. *Evolution of T_{pro} during the 30 year period.*

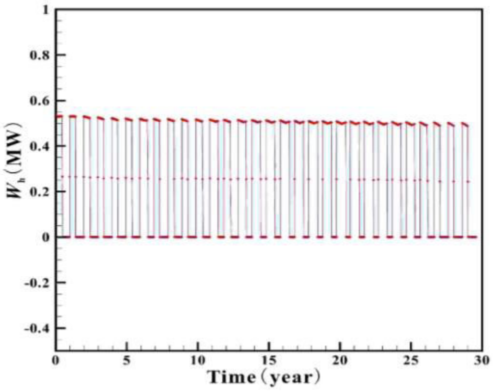

Fig.5. *Evolution of Wh during the 30 year production*

3.2.3 Energy efficiency

The energy efficiency of the system η_h is defined as the ratio of the total produced thermal energy to the internal energy consumption.

The calculated energy efficiency variation is illustrated in Fig.6. At the beginning of first heating season, η_h flashily reaches a maximum value of 180, and then begins to drastically decline to the final level of 68 in the end. This change pattern is same to the all following heating season. During the whole operation period, the energy efficiency slightly proceeds to decline, from 68 to 52, which is far higher than 1 showing a very favorable economic performance.

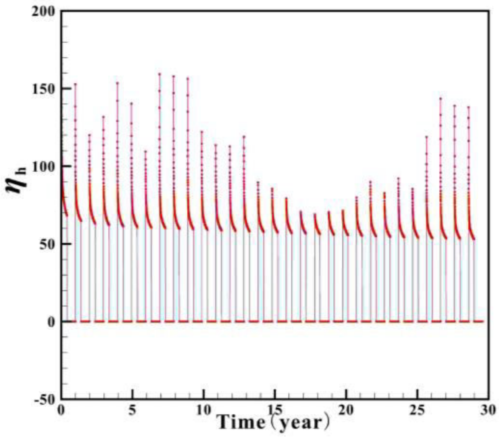

Fig.6. *Evolution of energy efficiency during the 30 year period.*

4 Conclusions

To technologically investigate the feasibility of the MLEGHP in cold regions just for winter heating, a case study in Shenyang city (northeastern China) is conducted, the following can be concluded:

(1) The results of fracturing simulation show that the fracture was restricted in the formation of 2200-2400m; the fracture half-length is 432m, the height is 200m and the width decreases from 0.350 to 0 cm from injection point to fracture edge; the fracture conductivity decreases also from 900 to 0 mD•m accordingly; the average fracture permeability is calculated as 257D.

(2) In the whole operation time, T_{pro} maintains at initial reservoir temperature of 69°C since the production begins, and this stage lasts for the first 2 years. From the 2th year, T_{pro} gradually declines from 69°C until to the final 63.8°C and corresponding reservoir temperature near the production well decreases from 69°C to final 65.4°C. The results show that the production water temperature is still very high after 30 year operation which could continuously support a good performance of surface heat pump system.

(3) W_h just slightly declines from 0.53MW to final 0.50MW in the whole production process. So during the whole life of the MLEGHP system, heat production keeps almost at constant and the thermal energy is steadily extracted out. During the whole operation period, η_h slightly proceeds to decline, decreasing from 68 to 52, which is far higher than 1 showing a very favorable economic performance.

In conclusion, the proposed MLEGHP system is a system that can potentially be used to eliminate the underground thermal imbalance and maintain efficient operation of the heat pump unit during long-term operation in cold regions.

Unit conversions:

Permeability: 1 D = 9.869233×10^{-13} m^2

Acknowledgements

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