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Electricity generation and heating potential from enhanced geothermal system in Songliao Basin, China: Different reservoir stimulation strategies for tight rock and naturally fractured formations

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ABSTRACT

Daqing City in Northern Songliao Basin (China) requires huge amounts of electric power and thermal energy for oil processing and resident support each year. We used actual geological and logging data of deep well YS-2 in Daqing oilfield to investigate electricity generation and heating potential from enhanced geothermal systems in tight rock and naturally fractured formations (3850–4500 m) using different reservoir stimulation methods. We then proposed optimized hydraulic fracturing and heat extraction strategies for each formation. Results indicate that the Yingcheng formation is suitable for the development of HDR (hot dry rock) resources in this region. Heat output in the stimulated naturally fractured formation is obviously higher than that in the tight rock formation. The development of HDR resources in the naturally fractured formation should be prioritized. In middle-low temperature (about 160 °C), tight rock formation still has great potential for heating supply, but the structure has poor capacity for electricity generation because of the low appropriate injection rate resulting from low reservoir temperature. However, when a high temperature reservoir is selected, electricity generation is feasible from tight formation by using gel-proppant hydraulic fracturing combined with horizontal well technology.

1. Introduction

The Daqing oilfield in Northern Songliao Basin, China (Fig. 1), possesses the largest sandstone-type hydrocarbon deposits on earth. The annual crude oil output of the Daqing oilfield is around 50 million tons, accounting for approximately 47% of China's annual onshore oil production [1]. In Daqing, huge amounts of hot water (>50 °C), in addition to electricity, are required for oil extraction and processing (e.g., oil displacement efficiency decreases by 2%–8% when injection water temperature is below 50 °C [2]) and for residential space heating (a long heating period of up to 7 months, with a heating temperature of 30–50 °C [3]).

However, for the past 50 years, more than 90% of the energy consumption of the Daqing area originates from fossil fuel combustion, which causes severe environment impacts, such as the "haze" phenomenon. Meanwhile, oil production has been decreasing annually, and the water content of many wells has reached more than 90% after decades of exploitation [4]. Therefore, a clean and huge resource potential energy to replace fossil fuels is urgently needed.

Geothermal energy is a clean and renewable energy source that can be developed to generate electricity and supply heat. The Daqing oilfield area possesses several potential features for geothermal development. The area is characterized by extensional tectonics, a thin crust of 29 km, a high regional heat flow of 70–90 mW/m^2 (as shown in Fig. 1), and a high geothermal gradient of 40–60 °C/km [7]. The presence of a thick (2–5 km) high-conductivity layer with low resistivity and low density indicate that a magma chamber reservoir serves as the heat source for the thermal anomaly [8,9]. Temperature at different depths in this area ranges from 39 °C to 60 °C at a 1 km depth, from 75 °C to 140 °C at 2 km, from 108 °C to 136 °C at 3 km, and from 144 °C to 180 °C at 4 km [8].

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Nomenclature

C_L	leak-off coefficient, 10^{-4} m $min^{-0.5}$
E	young's modulus, MPa
FG	fracture pressure gradient, MPa/m
I_R	flow impedance, MPa/(kg/s)
K	permeability, D
K_f	fracture permeability, D
K_{IC}	fracture toughness, MPa·$m^{0.5}$
P_{inj}	injection pressure, MPa
P_{injsur}	injection well surface pressure, MPa
q_{injmax}	maximum injection rate, kg/s
T_f	fracture flow conductivity, mD·m
W_e	electrical power, MW
W_h	heat production power, MW
ρ	density, kg/m^3
ν	poisson's ratio
σ_V	vertical stress, MPa
σ_H	maximum horizontal stress, MPa
σ_h	minimum horizontal stress, MPa
σ_{hmin}	minimum σ_h, MPa
D	darcy
gel-TS	gel-proppant tensile stimulation
inj	injection
max	maximum
min	minimum
n	porosity
pro	production
water-SS	water shear stimulation

However, only four hydrothermal geothermal fields are currently used for irrigation and bathing. The huge amounts of deep geothermal resources are not exploited for applications [9]. The large numbers of abandoned wells can be used to develop deep geothermal energy in a cost-effective manner. Only a small amount of ancient sedimentary water is available in the formation below 3 km, and these rocks are commonly called HDR (hot dry rock). EGS (Enhanced geothermal system) technology is an efficient way to extract thermal energy from HDR [10].

The effectiveness of reservoir stimulation directly determines the heat production ability from the EGS. Since the 1970s, many EGS project cases have proven this point, including Los Alamos, Ogachi, Horijiri, Rosemanowes, Soultz, Cooper Basin, and Desert Peak [11]. Hydraulic (gel-proppant fracturing and water fracturing), chemical, and thermal reservoir stimulation techniques are currently available to stimulate existing fracture networks and/or create new fractures [12]. In this study, we adopt hydraulic stimulation treatments because they are the main techniques used in EGS project.

In general, most oil wells in this region are drilled between 2000 m and 4000 m. In this range, the medium-low temperature geothermal resource (90–150 °C) is the major resource pattern. To successfully extract this resource, optimized designs must be constructed for a feasible and economical reservoir stimulation and heat extraction strategy compared with the high-temperature EGS in granite. Hofmann et al. [12] simulated different hydraulic fracturing and resulting reservoir scenarios from granitic basement rocks (100 °C) in Fort McMurray to find suitable fracturing strategies and conditions for oil sand processing. Van der Hoorn et al. [13] conducted a similar study by using hydraulic fracturing treatments for two limestone EGS projects in the Netherlands. Zhang et al. [14] investigated the electricity generation from EGS in Songliao basin by circulating oilfield-produced water through a reservoir (160–180 °C) stimulated by staged fracturing.

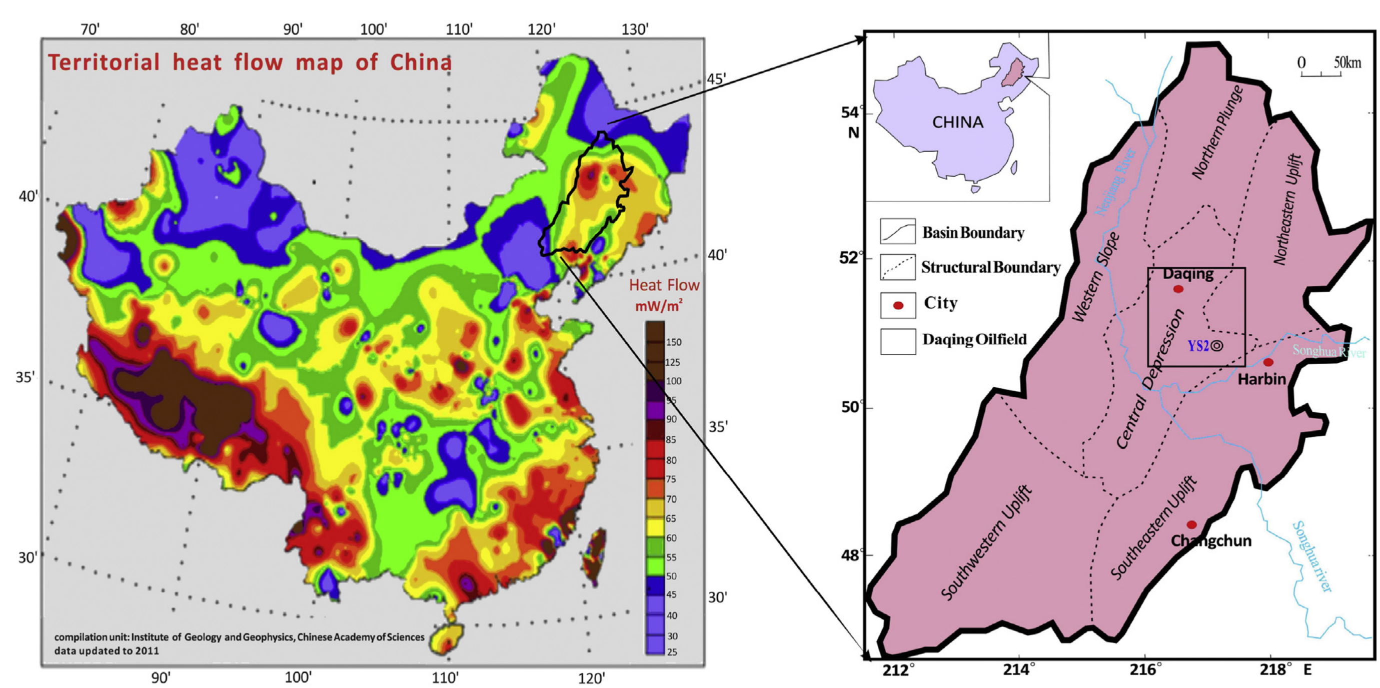

Fig. 1. Territorial heat flow map of China showing high heat flow of 65–100 mW/m^2 in Songliao Basin (left) [5]; Songliao Basin structure map indicating the location of Daqing oilfield, Daqing City, and YS-2 well (right) [6].