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Investigation on geothermal water reservoir development and utilization by variable temperature regulation: a case study of China

Hui Xie
School of civil and resource engineering
University of Science and Technology Beijing
Beijing, China
xiehui20000@sina.com

Luyi Zhang
School of civil and resource engineering
University of Science and Technology Beijing
Beijing, China
18813050023@163.com

Ruifei Wang
College of Petroleum Engineering
Xi'an Shiyou University
Xi'an, China
sirwrf2003@163.com

Hongqing Song
School of civil and resource engineering
University of Science and Technology Beijing
Beijing, China
songhongqing@ustb.edu.cn

Huifang Fan
School of civil and resource engineering
University of Science and Technology Beijing
Beijing, China
fanhuifang@ustb.edu.cn

Li Du
Sinopec Star Petroleum Co.
Beijing, China
duli.xxsy@sinopec.com

Pengguang Sun
Sinopec Star Petroleum Co.
Beijing, China
sunpegngunag.xxsy@sinopec.com

Abstract—Geothermal heating technology is critical in urban sustainable development and climate change mitigation. This research paper conducts a numerical simulation and multi-objective optimisation for geothermal heating systems based on factors such as ground demand, profitability regulation modes, and region areas. It's indicated that well spacing and production rate are the two main factors affecting production performance as well as emission reduction efficiency of geothermal heating systems. The heating mode also plays a vital role in the utilization of geothermal reservoirs. There is a delay in the formation time of thermal breakthroughs of the regulated geothermal heating system. The radius of the cold front shrinks, while production performance and emission reduction efficiency also decrease. Comparing the regulated geothermal heating system to the unregulated geothermal heating system, the construction investment of geothermal wells and the annual water consumption both decrease by up to 30% and 60%, respectively. Additionally, electricity costs increase by 5% to 25%. The regulated geothermal heating system with well spacing of 300m and production rate of 100m^3/h generates the highest efficiencies in terms of heat production, emission reduction, and economic performance, all of which are most suitable for this project in Qingfeng. The simulation method and optimisation model of this research paper can be extended to other regions.

Keywords—Geothermal heating systems, Variable temperature, Constant temperature, Emission reduction, Regulation mode, Heat extraction, Water consumption.

I. Introduction

Energy plays a vital role in the sustainable development of a country. However, the exploitation and utilisation of energy are the main sources of environmental pollution. For example, fossil fuels cause urban air pollution, acid rain, and worsen the greenhouse effect [1]. Fossil fuels are the main energy source in the world, especially in developing countries [2]. Therefore, it is urgent and necessary to convert from the current energy system that is reliant on fossil fuels to a sustainable energy system based on renewable resources. Geothermal heating technology uses geothermal resources for heat supply, which promotes the sustainable development of green buildings.

To date, there are 78 countries using geothermal energy [3]. With the popularization of geothermal heating technology, researchers studied the energy production process of the geothermal heating system. Kewen Li and Roland N. Horne [4] established preliminary mathematical models to calculate the geothermal reservoir's drainage as well as imbibition steam-water capillary pressure. S.N. Pandey et al. [5] used FEHM to simulate the evolution of reservoir transmissivity via the Thermo-Hydro-Mechanical (THM) model. Alastair Mcdowell et al. [6] employed TOUGH2 to simulate heat extraction in the geothermal heating system and discovered that viscous fingering occurred at low re-injection rates.

In the existing research, some scholars performed an economic evaluation on geothermal energy utilisation. Jason Phillips [7] applied a mathematical model to evaluate the potential level of a geothermal power plant. Paschalis Dalampakis et al. [8] concluded that geothermal energy was an efficient and economically valuable form of heating energy through quantitative and financial analysis. Konstantinos P. Tsagarakis [9] conducted an in-depth economic evaluation of a shallow geothermal energy system.

However, these research studies failed to consider three key issues included in our analysis, which affect the correctness of the simulation results. Research studies [4-6] discounted the regulation mode of geothermal heating system, only the constant temperature mode was applied.

Second, the operation modes of geothermal heating system were not refined in the economy analysis [7-9]. The results lacked validity and universal applicability. Lastly, the efficiencies of heat extraction as well as emission reduction of geothermal heating systems were not emphasized.

This academic paper investigated the following aspects: First, it established the hydrothermal-mechanical coupling mathematical model and the multi-objective optimisation of geothermal heating system. It subsequently combined geothermal reservoir data from Qingfeng county, and a comparative analysis of the differences between the geothermal heating systems with and without variable temperature regulations were performed. The influences of well spacing, production rate, and regulation mode on heat extraction and emission reduction capacity of geothermal heating systems were also analysed. Moreover, the production parameters were optimized based on ground demand and operation regulation modes. Finally, through multi-objective optimisation, the most suitable and economical geothermal heating system and its operating parameters were selected for Qingfeng county.

II. Study Area

According to a geological investigation conducted by China Petroleum and Chemical Corporation, the geothermal resources of Qingfeng is regarded as consisting of homogeneous porous media with high permeability. This project mainly uses Neogene reservoir, which is located between 900m to 1300m deep. The well production temperature is between 313.15K to 323.15K. The porosity of sandstone is greater than 20%, with permeability of up to 120 millidarcies. It is predicted that all geothermal water can be re-injected to the underground.

The underlying principle in this case involves multi-stage utilisation. Multi-stage utilisation of geothermal resources is achieved through heat pump application. In the entire process, geothermal water is only used for hot carrier transport. Cold water is re-injected into the underground reservoir to realise zero liquid discharge.

Variable temperature regulation is employed in the secondary heating system network (heating cycle). This regulation mode adjusts heat supply by regulating water supply temperature. At each stage, the circulating water flow remains unchanged and the supply temperature is regulated in accordance to the outdoor environment [10-11]. The management of variable temperature regulation is simple and convenient. In this operation mode, the heating pipe network attains hydraulic and thermodynamic balance.

III. Methodology

A. *Mathematical Model for Geothermal Reservoir*

The thermal-hydraulic-mechanical model is used to obtain the state of the geothermal reservoir after long-term fluid extraction and re-injection. The governing equations relating to heat extraction from geothermal reservoirs include three parts, namely: mass conservation, energy conservation, and displacement equation, as shown in (1-3) [12-14]. The process of modeling and theoretical analysis consists of the following assumptions [12-14]:

(1) As the microstructures are well connected, thus, the hydraulic and transport characteristics of the rock matrix can be described by averaged quantities.

(2) Local thermodynamic equilibrium is assumed between liquid phase and solid phase.

(3) There is diffusion, convective and conductive heat transfer in porous media.

$$c_t \phi \rho \frac{\partial p}{\partial t} + \nabla \cdot (\phi \rho_f (u_{fs} + u_s)) = Q_f \quad (1)$$

$$\rho c_p \frac{\partial (T)}{\partial t} + \nabla \cdot (-\lambda \nabla T) + \rho_f c_f u_{fs} \nabla T = 0 \quad (2)$$

$$\nabla \cdot \sigma = 0 \quad (3)$$

where ϕ is rock porosity; ρ_f is water density (kg/m^3); t is time (s); Q_f is the mass flow of sink/source item (kg/(m^3•s)); ρc_p is the heat capacity of porous media (J/(m^3•K)); T is temperature (K); λ is the thermal conductivity of porous media (W/(m•K)); σ is the typical Cauchy stress tensor; p is fluid pressure (Pa); c_t is total compressibility (Pa^{-1}), $c_t = c_f + c_s$; c_f is water compressibility (Pa^{-1}); and c_s is rock compressibility (Pa^{-1}); and u_{fs} is fluid flow velocity between rock and water flow (m/s). Both the heat capacity and thermal conductivity of porous media can be estimated as an arithmetic mean of each phase property weighted by its volume fraction.

In order to specify the solution for the above equations, prescribed pressure, prescribed fluid flux and prescribed temperature are considered in mathematical model. The finite element method is used in Open-GeoSys (OGS) to provide numerical solutions to the aforementioned coupled formulation [14].

B. *Emission Reduction Efficiency*

According to the survey provided by Sinopec Corp, coal usage is 11.80 kg for the geothermal heating system. For the coal-fired heating system, approximately 44.90 kg of coal is used [15]. Burning 1 kg of Chinese standard coal emits 0.034 kg of SO_2, 0.011 kg of NO_x, and 2.449 kg of CO_2. Table 1 summarizes the pollutant emissions related to the geothermal heating project and the coal-fired project, which produces 1GJ thermal energy [16].

TABLE I. Comparison of pollutant emissions for the geothermal heating project and the coal-fired project which product 1GJ thermal energy

	Geothermal project	**Coal-fired project**
Coal usage (kg)	11.80	44.90
SO_2 emission (kg)	0.40	1.52
NO_x emission (kg)	0.13	0.49
CO_2 emission (kg)	28.9	110.00
Total emission (kg)	29.43	112.01
Emission reduced (kg/GJ)		82.58

The emission coefficient of the geothermal heating system is calculated by (4).

$$PEG = COEF_{CO2} + COEF_{SO2} + COEF_{NOx} \tag{4}$$

Where $COEF_{CO2}$ is the emission coefficient of CO_2 per kilogram of standard coal; $COEF_{SO2}$ is the emission coefficient of SO_2 per kilogram of standard coal; $COEF_{NOx}$ is the emission coefficient of NO_x per kilogram of standard coal; PEG is the emission coefficient of the geothermal heating system.

Based on the mathematical model and coupled with (1-2), the production temperature T_P is calculated. Equation (5) computes the heat output of the geothermal heating system.

$$Q_P = q_f \cdot \rho_f \cdot c_f \cdot (T_P - T_0) \tag{5}$$

Where Q_P is the heat output of geothermal heating system (J/s); q_f is the production rate of geothermal heating system (m^3/s); ρ_f is water density (kg/m^3); c_f is the specific heat capacity of water (kJ/(kg•K)); T_P is the production temperature (K); T_0 is re-injection temperature (K).

The calculation formula for the emission reduction capacity of the geothermal heating system is described in (6).

$$M = 1\times10^{-9} \times PEG \times Q_P \tag{6}$$

Where M is the emission reduction efficiency of geothermal heating system (kg/s).

C. Multi-objective Optimisation Model

This research paper evaluates the economy of the geothermal heating system using payback period as the main criterion. This geothermal heating project has a single source of profit, which is warm income. It is assumed that net annual revenue after project operation remains the same. The calculation method is simplified to (7) [17].

$$Pt = \frac{K}{A} \tag{7}$$

Where Pt is the static payback time (year); K is the total construction investment (k USD); A is the net income of each year(k USD).

The overall optimisation goal is to obtain the most profitable and clean geothermal heating system. The optimisation function in this research paper is shown in (8). This multi-objective optimisation model is employed to assess the project in different regions to obtain the optimal geothermal heating system.

Optimization function: $\min Pt(x_1, x_2, x_3 .... x_n)$ (8)

$\min l(x_1, x_2, x_3 .... x_n)$

$\max M(x_1, x_2, x_3 .... x_n)$

Constraint condition:

Geological constraint $q_x \le q_{pmax}(x_1, x_2, x_3 .... x_n)$

Load constraint $Q_x \ge Q_l(x_1, x_2, x_3 .... x_n)$

Service life $T_x \ge T_{min}(x_1, x_2, x_3 .... x_n)$

Where q_x is the design value of production rate (m^3/h); q_{pmax} is the maximum of production rate (m^3/h); t_h is preset reinjection temperature (K); T_x is geothermal heating system service life (year); T_{min} is the minimum service life of policy (year); Q_x is the design value of system load (W); $x_1, x_2, x_3 .... x_n$ represent different working conditions.

Because of the limited project area, well spacing should be strictly controlled during the geothermal heating system design Second, due to the different levels of groundwater resources in different regions, the production rate of the geothermal heating system needs to be determined by the local test well data. Finally, the geothermal heating system should have good environmental adaptability to cope with extreme weather.

IV. RESULT DISCUSSION

Geological investigations provided by China Petroleum & Chemical Corporation (Sinopec Corp) are shown in Table 2. Previous literature[14] presents a simple doublet well scheme, including a re-injection well and a production well. Two regulation modes are distinguished in the simulation, namely: a geothermal heating system with variable temperature regulation (RGHS) and a geothermal heating system with constant temperature regulation (UGHS). In consideration of the local periodic heating law, the annual heating duration is 100 days and the geothermal wells are closed during rest time. Results from the final time step at the end of 50 years are analyzed in the next section.

TABLE II. THERMAL-HYDRAULIC-MECHANICAL PARAMETERS OF GEOTHERMAL RESERVOIR IN QINGFENG

Property	Value	Property	Value
Thickness of the reservoir	200m	**Porosity**	20%
Storage temperature	323.15K	**Rock density**	2600kg/m^3
Storage pressure	1400pa	**Rock heat**	878J/kg·K
Water density	980.4kg/m^3	**Water compressibility**	4.5×10^{-10} pa^{-1}
Water viscosity	5.494×10^{-4} m^2/s	**Rock compressibility**	4.3×10^{-10} pa^{-1}
Water heat	4185.4J/kg·K	**Thermal expansion coefficient of rock**	3.0×10^{-5} K^{-1}
Thermal conductivity of rock	3W/(m·K)	**Thermal conductivity of water**	0.6W/(m·K)
Rock poisson's ratio	0.1	**Permeability**	120mD

A. Effect of Well Spacing

This section studies the influence of well spacing on heat extraction as well as emission reduction of geothermal systems by inputting different well spacings (200m, 400m, and 600m) into the model. The remaining parameters are as follows: production rate is 100m^3/h and re-injection temperature is 288.15k. Figure 1 shows pressure distribution, temperature distribution, and emission reduction efficiency of the production well under these three conditions.

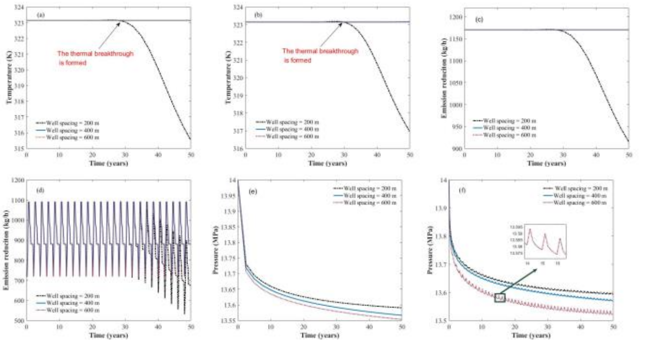

Fig. 1. Time evolution of production well for geothermal heating system with production rate of 100 m^3/h (a) Temperature at the production well of UGHS (b) Temperature at the production well of RGHS (c) Emission reduction efficiency of the production well of UGHS (d) Emission reduction efficiency of the production well of RGHS (e) Pressure at the production well of UGHS (f) Pressure at the production well of RGHS

It can be observed from Figures 1(a), 1(b), 1(c), and 1(d) that the temperature and emission reduction capacity of production wells with well spacing of 400m and 600m remain constant during the simulation period. The reason is because there is no thermal breakthrough under these scenarios. Comparing Figures 1(a) and 1(b), when well spacing is 200m, the production temperature of the geothermal heating systems in both regulation modes decreases. The implication is that the movement of the cold front has reached the production well. Figure 1(b) indicates that for the regulated geothermal heating system, the formation time of thermal breakthrough is delayed. Moreover, the final temperature drop is significantly less than that of the unregulated geothermal heating system.

No matter which kind of regulation mode is adopted, the emission reduction capacity of the geothermal heating system begins to decline when the production temperature declines. Comparing Figures 1(c) and 1(d), the emission reduction capacity of the regulated geothermal heating system is obviously weaker than that of the unregulated geothermal heating system. In Figure 1(d), the emission reduction curves exhibit a regular zigzag pattern. The pressure curves in Figure 1(f) also follow the same pattern. The reason is because both heating load factor and time weight are applied in the simulation of the geothermal heating systems with variable temperature regulation. As production rate and re-injection temperature vary with load and time factors, both pressure curve and emission reduction curve exhibit regular changes.

As observed from Figures 1(e) and 1(f), the pressure at the production well gradually decreases with increasing well spacing. Groundwater flows to low pressure areas by pressure gradients between the production well and the re-injection well. The decrease of pressure at the production well results in a decrease of the replenishment capacity of the re-injection well as well as the slow the movement of the cold front. The pressure drop of the regulated geothermal heating system well is evident, especially in the case of large well spacing.

Well spacing is an important parameter in determining the locations of geothermal production wells and re-injection wells. Small well spacing leads to premature thermal breakthrough and low heat extraction and emission reduction efficiencies. Building structure characteristics, project area, economy, policy, and equipment bearing capacity should be comprehensively examined for optimisation of well spacing in geothermal heating systems.

B. Effect of Production Rate

In the first part of the analysis, production temperature notably decreases when well spacing is 200m and re-injection temperature is 288.15k. Therefore, those parameters assist in visualising the influence of production rate on thermal breakthrough. Different production rates (80m^3/h, 100m^3/h and 120m^3/h) are encoded into the model, and the simulation results are indicated in Figure 2.

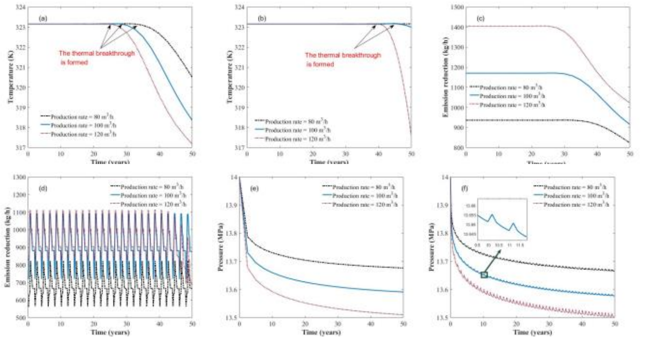

Fig. 2. Time evolution of production well for geothermal heating system with well spacing of 200m (a) Temperature at the production well of UGHS (b) Temperature at the production well of RGHS (c) Emission reduction efficiency of the production well of UGHS (d) Emission reduction efficiency of the production well of RGHS (e) Pressure at the production well of UGHS (f) Pressure at the production well of RGHS

As shown in Figures 2(a) and 2(b), in comparison to the unregulated geothermal heating system, the formation time of thermal breakthrough is delayed, and the final temperature drop is also significantly reduced. For both types of geothermal regulation modes, the increase in production rate speeds the movement of the cold front. The times of thermal breakthrough are significantly different among variable geothermal heating systems.

The emission reduction efficiency of the geothermal heating system is positively correlated with production rate and production temperature. Figure 2(d) signifies that in the first 40 years, the production temperatures of the regulated geothermal heating systems remain constant, and the emission reduction efficiency of each system presents a regular change. The larger the production rate, the stronger the emission reduction capacity. In general, the regulated geothermal heating system has a weaker emission reduction capability than the unregulated geothermal heating system.

As indicate in Figures 2(e) and 2(f), the pressure gradient between the production well and the re-injection well decreases with increases in production rate. The curves share the same trend in both regulation modes.

In general, the larger the production rate, the more significant the cold front propagation and the lower the pressure at the production well. However, a large production rate translates to high heat extraction and emission reduction efficiencies. Moreover, the production rate directly determines the number of geothermal wells. The economic and emission reduction efficiencies of geothermal heating systems are improved through reasonable control if the production rate in accordance to local hydrogeological conditions.

C. Optimize the Geothermal Development Strategy

a) Optimal Production Parameters

The unregulated geothermal heating system with well spacing of 600m and production rate of 100m^3/h has been installed for use in Qingfeng county. The geothermal well effluent temperature is consistent with the simulation results. It is assumed that the simulation results are accurate. The optimal well spacings of various geothermal heating systems are obtained according to the geothermal reservoir simulation. Results are shown in Figure 3.

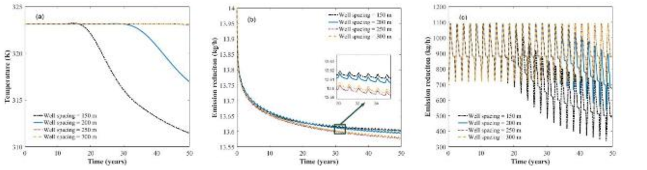

Fig. 3. Time evolution of production well for the regulated geothermal heating system with production rate of 100 m3/h (a) Temperature at the production well (b) Pressure at the production well (c) Emission reduction efficiency of the production well

Figure 4(b) shows that the cold front radius is approximately 260m in the regulated geothermal system with production rate of 80 m^3/h. Due to the uneven distribution of formation and unstable flow, the flow of low temperature groundwater is accelerated. It is recommended that minimum well spacing for this geothermal heating system should be 300m.

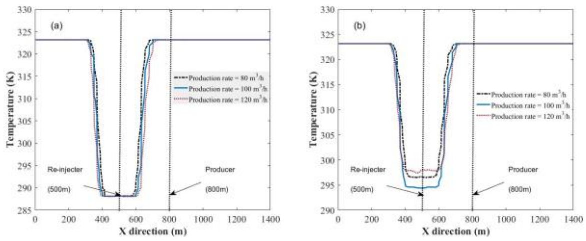

Fig. 4. Temperature profile along geothermal well at 50 years (a) Temperature profile along geothermal wells of UGHS (b) Temperature profile along geothermal wells of RGHS

TABLE III. THE OPTIMAL WELL SPACING FOR DIFFERENT GEOTHERMAL HEATING SYSTEMS

Type	Re-injection temperature	Production rate	Minimum well spacing
RGHS	288.15K	80 m^3/h	325m
		100 m^3/h	340m
		120 m^3/h	370m
UGHS	Variable temperature regulation	80 m^3/h	300m
		100 m^3/h	320m
		120 m^3/h	350m

The optimal well spacings of different geothermal heating systems are listed in Table 3. Optimal geothermal heating system cannot be solely determined by well spacing. Optimal heating mode and its production parameters are obtained via static technical economic evaluation and multi-objective optimisation model.

b) Optimal Production Parameters

After optimization of previous production parameters, it is guaranteed that geothermal heating systems will not break through in 50-year service life. As long as geothermal system does not have thermal breakthrough, geothermal well has high emission reduction capacity which meets the requirements of the policy. Finally, through economic calculations, geothermal system with the lowest payback period can meet the needs of this research. The construction costs, annual electricity and water consumption of different geothermal heating systems are calculated based on the number of geothermal wells, as indicated in Figure 5.

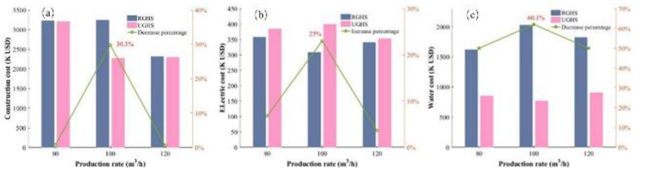

Fig. 5. The construction cost, annual electricity and water consumption of geothermal systems (a) The construction cost of geothermal heating systems (b) Electric cost of geothermal heating systems (c) Water cost of geothermal heating systems

Figure 5(a) shows that the construction cost of geothermal wells exhibits a downward trend with increases in production rate. The well construction cost of the regulated geothermal heating system with production rate of 100m^3/h is the lowest. In comparison to the unregulated geothermal heating system with the same production rate, well construction cost of the regulated geothermal heating system drops by 30%.

The heat provided by geothermal energy can't satisfy the building load. Therefore, the heat pump requires more power to absorb heat. It is shown in Figure 5(b) that the regulated geothermal heating system consumes more electricity than the unregulated geothermal heating system, with increases of up to 25%. The greater the electricity consumption, the greater the carbon emissions. However, even the most power-hungry geothermal system reduces carbon emissions by 60% as compared to boiler heating systems. Therefore, it is believed that in these six cases, geothermal systems clearly exhibit efficient emission reduction capabilities.

Figure 5(c) denotes that less geothermal water was consumed in the regulated geothermal heating system as compared to the unregulated geothermal heating system, saving close to 50%. This is a very important conclusion. Qingfeng county's geothermal resources are not abundant. Reducing the extraction of groundwater resources based on the case of meeting residential heating loads as well as the people's comfort requirements have a promotional significance on the geothermal heating technology. Therefore, the use of the geothermal heating systems with variable temperature regulation in areas with insufficient geothermal resources is recommended.

The rules of annual electricity consumption, water consumption, and initial investment in geothermal systems are not consistent. Therefore, a geothermal system with short payback period should be selected by coupling the initial investment, operational costs, and revenues, as shown in Figure 6.

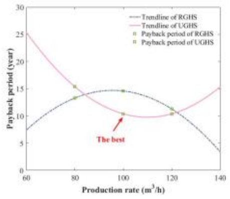

Fig. 6. The payback period of each geothermal heating systems

Figure 7 indicates that with increases in production rate, payback period of the unregulated geothermal heating systems decreases after an initial increase. The regulated geothermal heating system exhibits the opposite trend. In combination with Figure 5(b), the regulated geothermal heating system uses less water. The regulated geothermal heating system with production rate of $100m^3/h$ exhibits the highest heat production, emission reduction, and economic performance efficiencies, which is most suitable for this particular geothermal project. The mathematical model and optimisation model of this research paper may be directly applied to other geothermal systems.

V. Conclusion

The optimal operating modes and production parameters of geothermal heating systems have been evaluated by integrating the mathematical model and the multi-objective optimisation model. According to the results of this research study, the main conclusions and suggestions are as follows:

1. Well spacing and production rate are two main factors that influence production performance and emission reduction efficiency of geothermal heating systems. Small well spacings and large heat production rates lead to premature heat breakthrough.

2. For the regulated geothermal heating system, the formation time of thermal breakthrough is delayed. The production performance and emission reduction efficiency of geothermal heating systems decrease. However, the number of geothermal wells may be reduced relative to the unregulated geothermal heating system with the same production rate.

3. For the geothermal heating system with variable temperature regulation, the construction investment of geothermal wells is reduced by up to 30%. Annual water consumption is reduced by up to 60%, but electricity consumption costs increase by 5% to 25%.

4. Although both regulated and unregulated geothermal heating systems have similar payback periods, regulated geothermal heating systems use less underground water. During operations, these systems are able to maintain the hydraulic stability of pipe networks. This heating mode is a promising optimisation goal for environmental adaptability and building comfort by geothermal heating systems.

5. The regulated geothermal heating system with well spacing of 300m and production rate of $100m^3/h$ exhibits the highest heat production, emission reduction, and economic performance efficiencies, which are most suitable for the Qingfeng county project. The simulation method and the optimisation model of this research paper may be directly used in the simulation of heating projects in other regions.

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