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Assessment and Modelling of Sedimentary Geothermal Resources in North China

Huang Jiachao

Sinopec Green Energy Geothermal Development Co. Ltd., Xianyang 712000, Shaanxi, China

huangjiachao2008@163.com

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ABSTRACT

Low-temperature sedimentary geothermal resources are widespread in the continental regions of the Earth's crust. They are quite different in nature from the geothermal resources associated with volcanic systems or tectonically active regions of the crust. Their management during long-term utilization also requires somewhat different emphasis from that of the conventional geothermal resources. More examples of sedimentary resources, which have been utilized heavily for direct applications, can be found in China. More than 3500 geothermal wells had been drilled in China by 2010, most of them in sedimentary geothermal systems. Two Chinese sedimentary geothermal systems, the Xianyang system in Shaanxi and the Xiongxian system in Hebei Province have been assessed by lumped parameter pressure response modelling and volumetric calculations. They are of quite contrasting nature, the Xianyang system being a porous-type sandstone system and the Xiongxian system being a fissured-karst carbonate rock system. Xianyang lies in Wei River sedimentary basin in the center of China. The average permeability-thickness of the Xianyang reservoir is estimated to range from 2 to 7 Darcy-m through the lumped parameter modelling. The Xianyang sandstone reservoir appears to approach a closed reservoir in nature. The volume of geothermal fluid stored underground in the Xianyang territory is estimated to be $59•10^9$ m^3 and recoverable heat to be $13•10^{18}$ J. Xiongxian lies in the North China Basin at about 110 km and 100 km from Beijing and Tianjin, respectively. Large scale reinjection started in Xiongxian in 2009. The internal permeability-thickness of the Jixian reservoir in Xiongxian is estimated to be up to 95 Darcy-m, and the external permeability over 14 Darcy-m, according to the lumped parameter modelling conducted. The potential of the Jixian reservoir is rather promising for future exploitation, partly because reinjection should be easy. The pressure response of the Jixian reservoir is comparable to that of an open reservoir. The volume of geothermal fluid stored in the Jixian reservoir, in the Xiongxian territory, is estimated to be $9.6•10^9$ m^3 and the recoverable heat to be $2.5•10^{18}$ J. The lumped parameter models for the respective systems are used to calculate reservoir pressure predictions for different future production scenarios.

1. INTRODUCTION

Volcanic geothermal systems characterised with high temperature contain high-quality energy, but their distribution is subject to geographical limits. This would make the wide usage of geothermal energy restricted throughout the world. However, sedimentary geothermal systems are widely spread in most regions of the world, where most of the world population and economic activities are distributed. This combination makes the utilization of geothermal energy worldwide possible and beneficial for more people. Exploitation and utilization of sedimentary geothermal resources has been widely implemented all over the world. It has experienced a rapid growth in North China in the past few years.

Geothermal energy in China is mostly exploited from sedimentary geothermal systems. Those characterised with low-medium temperature resources prevail because population and economic activities are mainly distributed in eastern China where low-medium temperature resources are abundant. Sinopec Green Energy Geothermal Development Co. Ltd. (SGEG) was established in 2006. It has already set up district space heating networks in Xianyang, Shaanxi Province and Xiongxian, Hebei Province.

Lumped parameter models of the Xianyang and Xiongxian geothermal systems are set up (using the LUMPFIT software) to simulate pressure changes in the systems caused by long-term production, based on the local geological information, respectively. Lumped parameter modeling simplifies a geothermal system as a few tanks and flow resistors. It can solve geothermic and hydrological problem in a mathematical way through the application of computer software. Axelsson (1989) has described this efficient method, which tackles pressure change simulation in geothermal and other hydrological reservoir with lumped parameter models as an inverse problem and can simulate the data accurately, if the data quality is sufficient. The two typical sedimentary geothermal systems are mostly analysed on basis of the same theory and methods, which enables a convenient comparison. Data for Well Sanpu2, which are located in different geological structures of Xianyang geothermal system, are selected as representative for the modelling. A long production history data-series for the whole Xiongxian territory is also analysed in the paper. Three scenarios for different reinjection rates are set up for that system to estimate and compare the future water level changes.

2. XIANYANG SEDIMENTARY GEOTHERMAL SYSTEM

2.1 Case Background

Xianyang lies in the centre of Shaanxi Province in the People's Republic of China. It is around 25 km northwest of Xi'an, the capital of Shaanxi today. The prefecture-level division of Xianyang has 5 million inhabitants distributed among 13 counties. The metropolitan area of Xianyang has around 600,000 inhabitants.

The Xianyang geothermal system contains a rich low enthalpy geothermal resource. Since the first geothermal well was drilled in 1993 over 50 geothermal wells have been drilled (Some of their locations are presented in Figure 1), ranging in depth from 1464 to 4080 m, distributed throughout the region with reservoir temperature ranging from 55 to 120°C. New geothermal wells drilled in the past few years reach greater depths and are mostly around 3000 m deep, or even more. The reservoir pressure of most Xianyang wells has experienced a relatively stable decline since production started. The pressure of the wells the north of, or close to, the Wei River northern bank fault has declined 1.1-2.8 metres per year, but those in the south of Xianyang, close to the centre of the Wei River Basin, have declined more severely. Geothermal fluid produced from the Xianyang geothermal system is utilized for house heating in the metropolitan area of Xianyang and its administrative counties Xingping, Wugong, Liquan and Sanyuan, which are located in the southeast part of Xianyang. Geothermal fluid has been used for space heating during the wintertime, as well as for swimming, bathing and balneology. The geothermal space heating in Xianyang supplies heat from 16th December to 15th March of the following year, according to local space heating regulations. The rest of the year only a small amount of geothermal fluid is utilized for swimming and bathing.

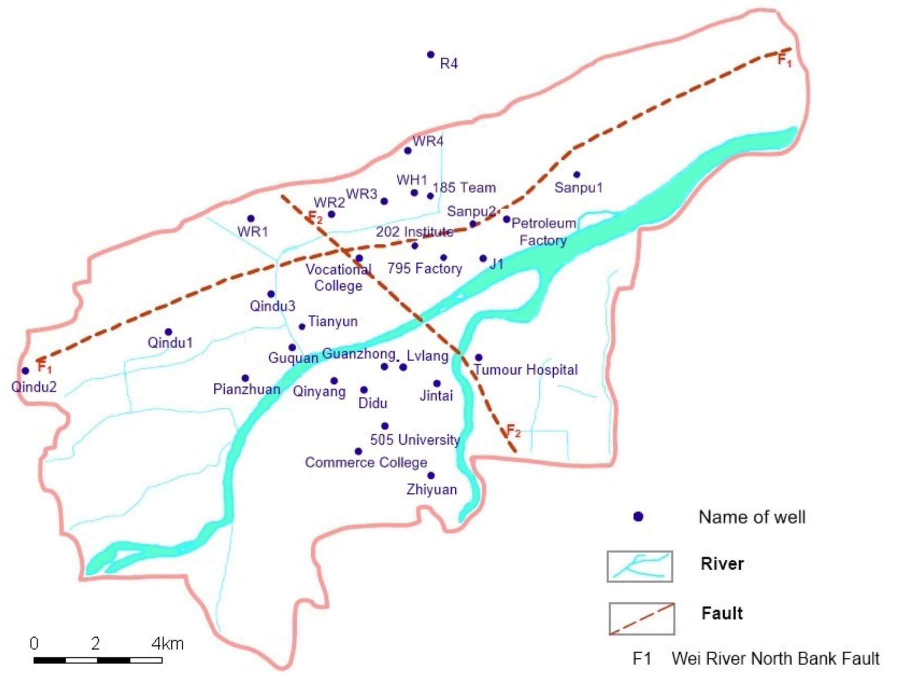

Figure 1: Location of Geothermal wells in Xianyang City presented in the paper

2.2 Modelling of Xianyang Geothermal System

2.2.1 Conceptual Reservoir Model

A conceptual reservoir model of the Xianyang geothermal system, which is a part of the Wei river sedimentary basin, is set up, based on geological structure and character. The conceptual reservoir model of the Xianyang geothermal system can be described as follows:

1) The rocks of the Quaternary Qinchuan group (Q_{2-4}qc) are considered as the caprock of the Xianyang reservoir. The thickness is in the range of 350-550 metres. The geothermal gradient in the caprock is distinctly higher than in the reservoir below.

2) The Upper Tertiary Zhangjiapo Formation (N_2^2z), Upper Tertiary Lantian-bahe Formation (N_2^1l+b) and Upper Tertiary Gaoling Group (N_1gl) are considered as the reservoir of the Xianyang geothermal system. These are composed of alternating sandstone and mudstone layers and the total thickness is in the range of 1780-3000m. The sandstones and mudstones in these formations are aquifers and aquicludes, respectively. Those alternating sandstone and mudstone layers are treated as a uniform reservoir in the following model simulation.

3) The Wei River Northern Bank Fault, Chang'an-Lintong Fault and Qinling Mountain Front Fault as well as the limestone which is beneath the Tertiary stratum and in the north of Wei River Northern Bank Fault are believed to contribute a weak recharge for the main production layer. The large-scale permeability structure of the Xianyang reservoir is, furthermore, partly controlled by these faults.

4) The Xianyang geothermal reservoir is a typical low temperature liquid-dominated sedimentary reservoir of the porous type. The average measured heat flux from the crust is 71.6 mW/m^2. And the geothermal gradient is 3.2-3.7°C/100m.

Xianyang city is located in the centre of the Wei River sediment basin and we only studied the reservoir in the metropolitan area of Xianyang administrative territory, so called Xianyang reservoir, but not the whole Wei River Basin. It is a typical confined liquid-dominated reservoir and is a part of the Wei River Basin. A significant feature of the system is the alternation of beds of sandstone and mudstone that widely exists in the Xianyang geothermal system. It is considered a single, uniform reservoir for the purpose of the study presented in this paper. The Wei River sediment basin is regarded as a reservoir with very weak recharge by most geologists in the region, so it will be simulated as both a closed and open reservoir in this paper. The Xianyang geothermal system will, furthermore, be regarded as a two-dimensional model in the following simulation.

2.2.2 Lumped Parameter Simulation

The production potential of a geothermal system is predominantly determined by the pressure decline due to production. If geothermal fluid and energy supply is sufficient, the pressure drawdown becomes a unique influencing factor for production capacity of a geothermal system. In order to evaluate the potential of the Xianyang geothermal system, lumped parameter models have been used to simulate and predict pressure variations in the system.

Wells Sanpu2, which is owned by SGEG, are selected for the simulation study due to the fact they have relatively long and complete monitoring data-sets, which are available. The well supply geothermal fluid for space heating in winter time, and provide tap water all year round.

Well Sanpu 2 (Figure 1) is drilled right at the Wei River Northern Bank Fault. This well is used for space heating in winter and for providing hot tap water throughout the year. Before exploitation in 2004 the initial well-head pressure of Sanpu2 was 5.0 bar. But later, or in the summer of 2009, a down-hole pump had to be installed in the well due to the increasing geothermal fluid extraction from the well and the decreasing pressure of the well, and the whole geothermal system. Well head pressure of well Sanpu 2 had dropped to -0.2 bar in 2011. It drops about 0.74 bar per year at an average discharge of 9.7 l/s.

A two tank open model and a three tank closed model are found to be the best fitting simulation models for well Sanpu 2. The two tank open model for Well Sanpu 2 has a coefficient of determination of 91.4% and a standard deviation of 0.574 bar, assuming the initial pressure to be 5.7 bar and the turbulence coefficient to be 0, which is slightly different from the actual conditions (5.0 bar and 0.0382 bar/$(l/s)^2$, respectively). The three tank closed model yields a coefficient of determination of 92.2% and a standard deviation of 0.552 bar. This is just a slight improvement over the two tank open model. Therefore, the two models are both applied to well Sanpu 2.

The conductance between the second tank and infinite outer reservoir in the two tank open models is obviously lower than that between the first and second tank. This implies that the geothermal reservoir has a poor hydraulic connection with outer geological bodies, but a much better permeability inside the reservoir.

2.2.3 Estimation of Xianyang Reservoir Properties

The properties of the reservoir being simulated, which is close to Well Sanpu 2, can be estimated on basis of the properties of the lumped parameter model by the equations from LUMPFIT. Firstly, temperature and porosity of the geothermal wells are estimated based on local geothermal well information. Then the reservoir thickness is estimated from data on the cumulative thickness of production layers, originating from well screen records. Consequently, the storativity of the reservoir can be estimated. The size of a model, such as volume, surface area and radius of reservoir, can be derived for both the two tank open model and three tank closed model. The estimated model size and permeability for Sanpu2 is consequently shown in Table 1. The first tank, second tank and third tank represent different parts of the reservoir that can be influenced by a single well.

It should be pointed out that permeability gotten from the simulation result is average permeability of sandstone and mudstone because the lumped model assumes that the alternating layers of sandstone and mudstone is one reservoir. In addition the estimated permeability is likely to be lower than the actual permeability of the Xianyang reservoir because of the assumption that the pressure change of each of the wells simulated is just induced by the production of the well itself, but not affected by other wells nearby.

Table 1: Reservoir properties of the Xianyang reservoir based on properties of lumped parameter models for Sanpu2

Size	Tank	Two Tanks Open	Three Tanks Closed
Volume (km^3)	First tank	1.9	1.1
	Second tank	37	12
	Third tank		32.0
	Total	39	46
Area (km^2)	First tank	1.4	0.82
	Second tank	27	9.0
	Third tank		23
	Total	28	33
Radius (km)	First tank	0.66	0.51
	Second tank	3.0	1.8
	Third tank		3.3
Permeability (mD)	Inner	4.4	5.0
	Outer	0.0090	1.9
Permeability-thickness (D-m)	Inner	6.1	6.9
	Outer	0.012	2.5

The radius of the model tanks implies the radius of hydraulic influence of each of the wells, which should also be considered when designing the interval between wells. The estimated permeability between the second tank and third tank of Sanpu2 shows that the hydraulic connection of the reservoir around the wells to the outer parts of the geothermal system is not so good.

2.2.4 Pressure Predictions

For the purpose of calculating the predictions a future production period of 15 years was appended to the input file. The prediction assumes maintaining the average production of the past few years, without any changes. Both an open model and a closed model were used for the predictions for the Xianyang reservoir response. The results for closed and open models represent two extreme conditions for lumped parameter modelling, and geothermal system, or pessimistic and optimistic scenarios. The real behaviour of a geothermal system would be somewhere between these two simulated responses. The difference between the predictions of open and closed models is noteworthy and also reflects the nature of the Xianyang system.

The two tank open model and the three tank closed model are shown to be the most proper lumped parameter models for Well Sanpu2. This well has a production of 9.7 l/s in the past seven years on average. The predictions are calculated assuming that the flow rate will be maintained. As shown in Figure 2, the open model gives a little more pessimistic forecast than the closed model. Normally an open model gives a more optimistic forecast than a closed one. This is not common in such predictions. The reason is that the conductor between the second tank and infinite outer reservoir in the two tanks open model is just $2.99 \cdot 10^{-7}$ ms, two orders of magnitude lower than that between the tanks in the three tanks closed model. Whatever model is used, the pressure decline trends are very close. The well head pressure will go down to -11.2 bar in the next 15 years according to the two tank open model. It declines 0.75 m annually. The three tank closed model predictions seem a little better and according to them the pressure will decline to -9.6 bar in 15 years. The modelling and prediction result indicate that the Xianyang reservoir seems to behave like a closed reservoir.

Actually, Well Sanpu2 is an artesian well when it was completed with a wellhead pressure in 2004. The wellhead pressure declines very fast due to exploitation of geothermal fluid. A pump had to be installed in the well to extract geothermal fluid in 2009. Water level of the well has gone down to underground. Consequently, it cannot go on to measure wellhead pressure any more. On the purpose of pressure drawdown expression without a break, a negative pressure is introduced during pressure prediction. A negative wellhead pressure means that water level of the well has gone down to underground in the paper. That means water level will go down to 112 m below ground for the two tank open model and 96 m below ground for the two tank open model in the next 15 years.

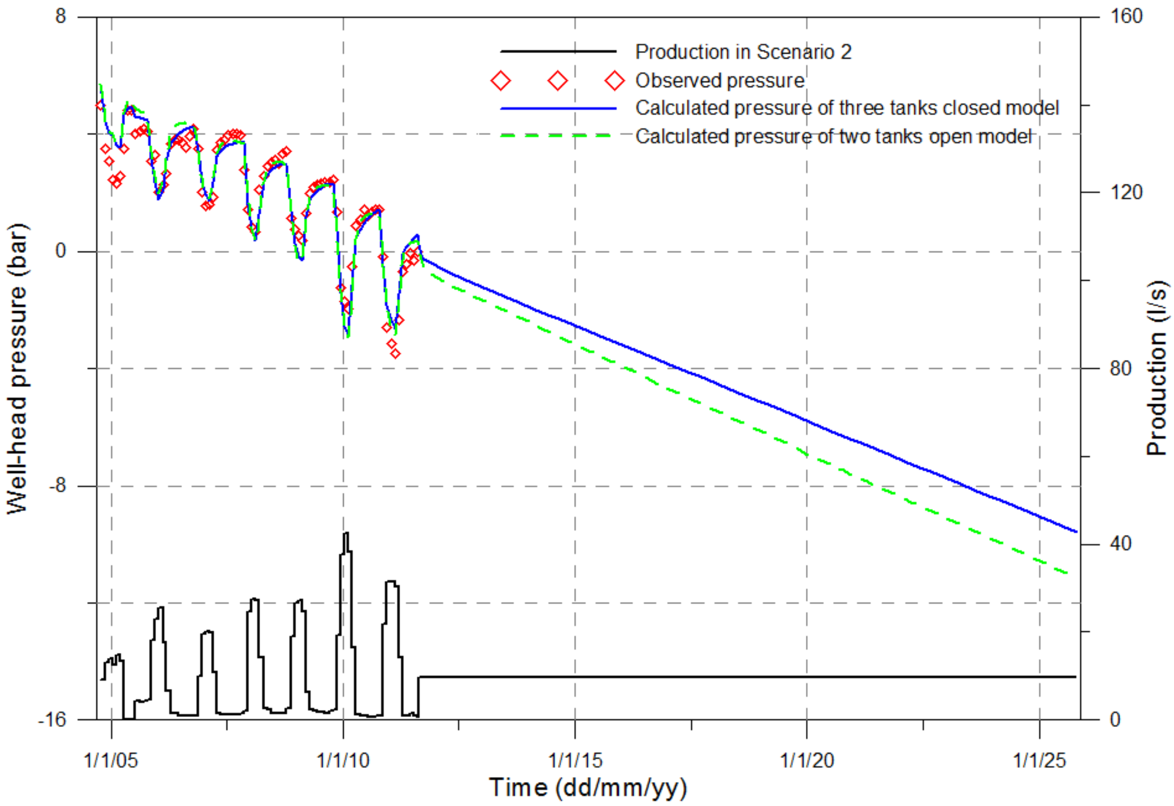

Figure 2: Comparison between pressure predictions of the closed and open models lumped models for well Sanpu 2

2.3 Geothermal resource assessment with volumetric method

The geothermal fluid volume and energy content of the reservoir in metropolitan area of Xianyang, including the Qindu District and Weicheng District administrative territories, are estimated. There is no new well targeting Zhangjiapo Formation in the last decade since temperature of well head extracting from Zhangjiapo Formation is lower and in the range of 50-60 °C. Bailuyuan Formation just distributes in the corner of southeast of Xianyang. Its depth is more than 3500 m and production is worse than the other formations. This formation is also not drilling target. Therefore, reservoirs in Lantian-bahe Formation and Gaoling Formation are available economically in the current condition and will be assessed in the section.

Applying volumetric method, the volume of geothermal fluid, the heat in the reservoir and the recoverable heat in the metropolitan area of Xianyang, are estimated to be $58.8 \cdot 10^9$ m^3, $50.3 \cdot 10^{18}$ J and $12.6 \cdot 10^{18}$ J, respectively. The exploitable volume of Xianyang reservoir, for the Lantian-Bahe and Gaoling formations, is $0.765 \cdot 10^9$ m^3.

3. THE XIONGXIAN CASE STUDY, CHINA

3.1 Case Backgroud

Xiongxian lies in the North China Basin where around a half of all geothermal wells of China are drilled. It is at a distance of 108 km from Beijing and 100 km from Tianjin. The number of inhabitants is 336 thousand and it covers an area of 524 km^2.

The Xiongxian geothermal reservoir is a typical fissured, karst reservoir. It is relatively shallow with the deepest geothermal well being 1800 m and the reservoir temperature ranging from 50 °C to 95 °C. The geothermal resource is mostly used for space heating. Geothermal utilization in Xiongxian began in the 1970s and around 70 geothermal wells (including 8 reinjection wells) have been drilled by 2014. Among them around 48 geothermal wells (including 18 reinjection wells) were drilled in 2009-2011. Well head pressure has dropped from 10 m water head above ground in the 1970's to about 70 m below surface now. Utilization of geothermal energy is concentrated as space heating, bathing and greenhouse agriculture while the average outside temperature in January is -4.7 °C. Similarly, the geothermal resource supplies heat from 16th December to 15th March of the following year, based on local space heating regulations. However, geothermal reinjection started in 2009 in the Xiongxian geothermal field. All fluid extracted from newly drilled geothermal wells has to be injected since 2009. Besides, some old production wells have been matched with new reinjection wells or have been switched to being reinjection wells. Full reinjection has been implemented just under the action of gravity on the fluid itself, without any pressure on wellhead.

3.2 Modelling of Xiongxian Geothermal System

3.2.1 Conceptual Model

The Xiongxian geothermal system is a part of the Niutuozhen Uplift whose basic structures are shown in Figure 3. Its conceptual model can be described and summed up as follows:

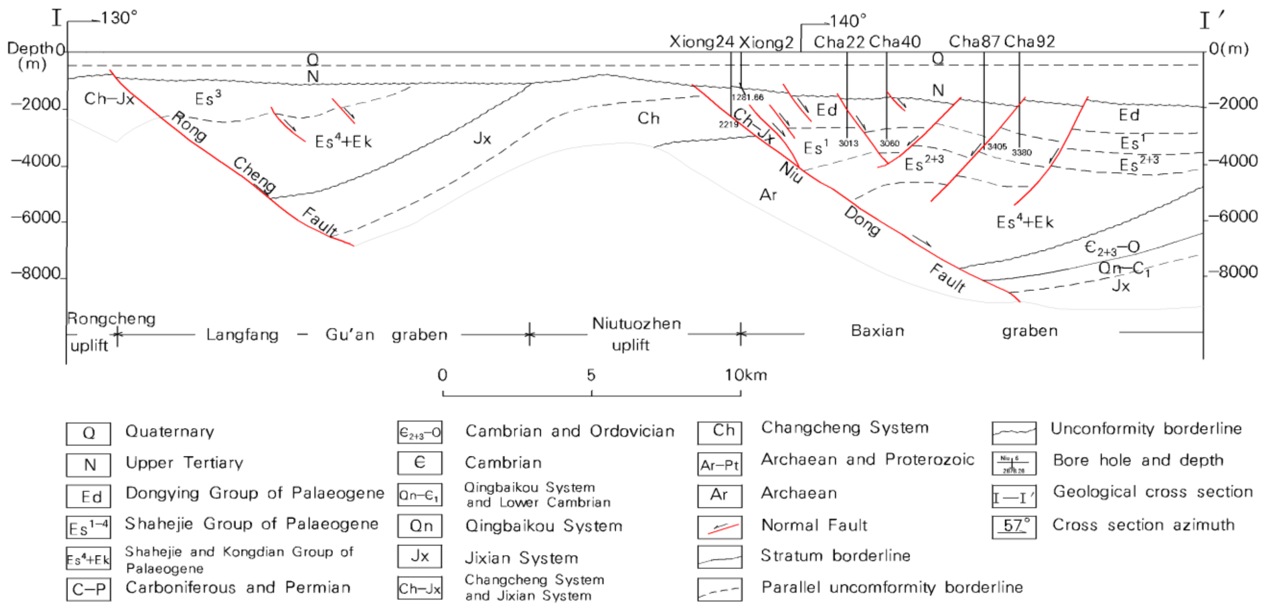

Figure 3: A geological cross-section through the Niutuozhen Uplift (Wang, 2009)

1) Quaternary strata provide the caprock of the Xiongxian geothermal system. Permeability of the strata is poor (10^{-1} mD) (Pang, 2010). The heat conductivity of the clay is 1.7-2.3 W/mK and lower than that of the Xiongxian geothermal reservoir below (Ma et al., 1990).

2) The Niutuozhen geothermal system consists of a Tertiary sandstone reservoir of the porous type and a Jixian System bedrock reservoir of the karst-fissure type. The two reservoirs extend through the whole Xiongxian territory. Limestone of Ordovician and Cambrian age also exists east of the Niutuozhen Uplift, but its utilization is not feasible economically since the depth of the reservoir is over 5000 m. The total thickness of the Tertiary reservoir sandstone is around 240 m. The effective thickness (the karst and fissure zone) of the Jixian reservoir is in the range of 285-315 m.

3) The Niudong, Rongcheng, Daxing and Niunan faults are looked upon as permeable boundaries of the geothermal system, which have relatively high permeability.

4) Recharge to the Jixian reservoir is believed to come from the faults surrounding the Niutuozhen uplift and as meteoric water originating in the mountains around North China Plain. The measured heat flux through the area can reach about 72-110 mW/m^2 (Chen, 1988). Average geothermal gradient in the Wumishan Formation of the Jixian System is 3.28°C/100m.

3.2.2 Lumped Parameter Simulation

The data-set of Xiongxian is a complete Xiongxian production and water-level history. This includes the historical geothermal fluid extraction data in the Xiongxian territory, composed of water level and total production from February 1982 to April 2004. The total production in this data-set includes the extraction from both the Tertiary sandstone reservoir and the bedrock reservoir. But it is treated as extraction from the bedrock reservoir only, because utilization of Tertiary geothermal fluid constitutes just a small proportion and the ratio between the reservoirs has been going down rapidly due to the much higher energy supply of wells exploiting the bedrock reservoir. And this is the reason why the calculated water level is significantly lower than the observed one during the first dozen of years.

The two tank open model and the three tank closed model simulation of the Xiongxian history are successful, with good fitting to the observed water level. The two models have a coefficient of determination of 97.2%. This means that the two calculated water level curves, by the two tank open model and three tank closed model, completely coincide. The past average production is assumed to be 0 in the simulation instead of 6.9 l/s in its reality. We can find κ_3 (storage capacitance of tank 3, a parameter of lumped model) is astonishingly big. This implies the recharge of Xiongxian reservoir would be astonishingly strong, also. That is, the reservoir almost behaves like an open reservoir.

3.2.3 Estimation of Reservoir Properties

The Tertiary and Jixian reservoirs in Xiongxian are typical low temperature geothermal reservoirs with liquid dominated characteristics. The fissure and karst evolution in the Jixian reservoir decreases downwards. Therefore it can simply be assumed that the effective thickness is within the top 500 m. A porosity of 6% is assumed appropriate for estimating the properties of the upper part of the Jixian System (Pang, 2010). Consequently we can treat the well as a fully penetrating well in two-dimensional flow. The estimated model size and permeability for Xiongxian Geothermal system is consequently shown in Table 2.

The estimated sizes can probably be explained as follows: The first tank of the Xiongxian history data likely represents the whole Xiongxian Jixian bedrock reservoir; The second tank may represent adjacent aquifers, such as the Tertiary sandstone reservoir above the bedrock reservoir; The third tank may represent aquifers in other nearby geological structures as presented in Figure 3, such as aquifers in the Baxian Depression. The most important highlight in this region is the exceptionally high average permeability estimated, which is up to 260-280 mD. Pang (2010) also calculated the effective permeability of the reservoir around Well 0902 in Xiongxian, which is in the range of 150-300 mD. This is the main reason why reinjection has been so successfully applied without any pumping pressure.

Table 2: The reservoir parameters of the Xiongxian reservoir based on lumped parameter model properties

Size	Tank	Two Tanks Open	Three Tanks Closed
Volume (km^3)	First tank	240	240
	Second tank	190	170
	Third tank		18000
	Total	430	18000
Area (km^2)	First tank	720	710
	Second tank	570	520
	Third tank		52000
	Total	130	54000
Radius (km)	First tank	15	15
	Second tank	20	20
	Third tank		130
Permeability (mD)	Inner	260	280
	Outer	7.1	43
Permeability-thickness (D-m)	Inner	88	95
	Outer	2.4	14

3.2.4 Water Level Predictions

Water level predictions were calculated based on the parameters of the lumped parameter models obtained. Three scenarios of production in Xiongxian are set up for the future 15 years. Scenario 1 assumes the 2009 production to be constant without any reinjection, which is equivalent to an extraction of 123 l/s. This scenario is set up only for comparison with the following two reinjection scenarios, since reinjection has actually been performed since 2009. Scenario 2 assumes that 50% reinjection (equivalent to 50% production) will be realized in the first five years since 2009, 85% reinjection (15% production) during the second five years and full reinjection (no production) during the third five year period. Similarly, scenario 3 assumes that 25%, 40% and 50% reinjection will be realized during the first, second and third five year periods, respectively. These scenarios and their net production are presented on Table 3. The last two cases both increase the ratio of reinjection gradually based on the current local extracting and injecting tendency. Scenario 3 seems to be too pessimistic and scenario 2 is more in line with the current reinjection tendency in Xiongxian. The three tank closed model and two tank open model acquired above are applied in this prediction since their determination coefficients are the same, and they yield pessimistic and optimistic predictions.

Table 3: Scenarios for water level predictions in Xiongxian

Scenarios		Net production (l/s)		
		2009-2014	2014-2019	2019-2024
Scenario 1	No injection	123	123	123
Scenario 2	Positive injection	61.5	18.5	0
Scenario 3	Negative injection	92.3	73.8	61.5

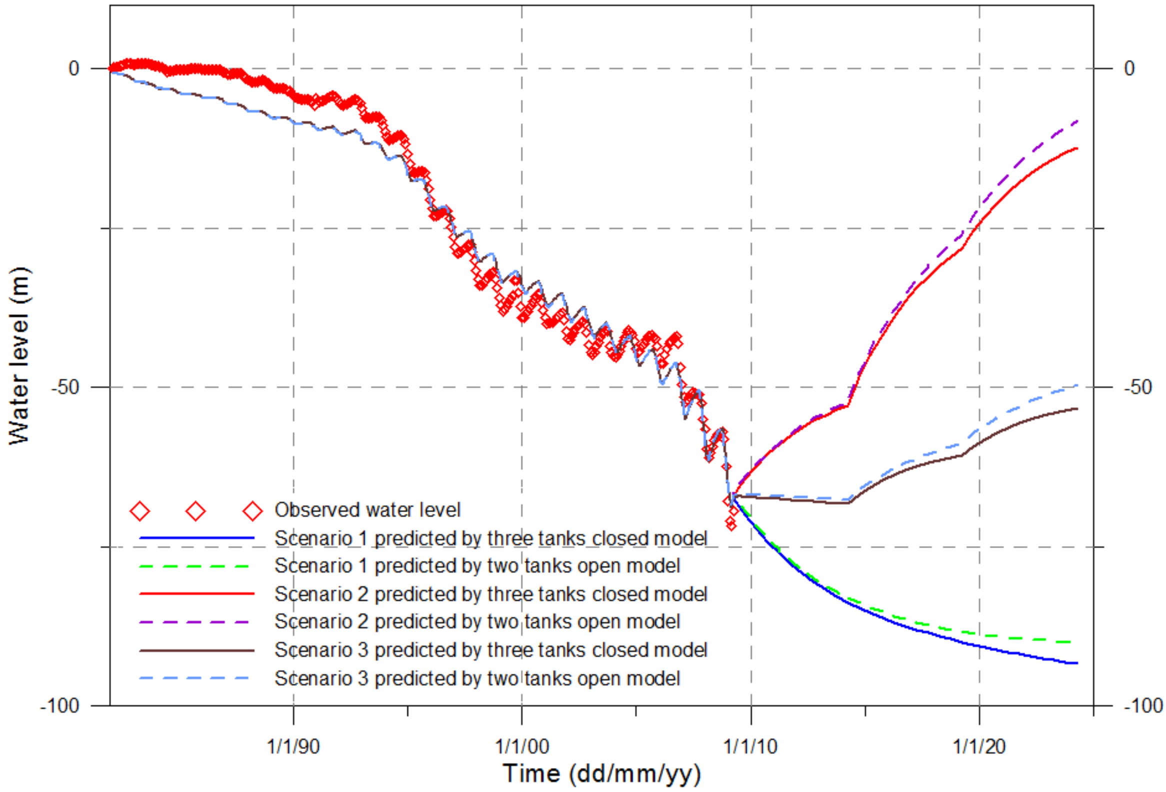

Figure 4: Comparison of water level prediction for different scenarios in Xiongxian

Water levels for scenario 1 will drop to -93 m and -90 m according to the three tank closed model and the two tank open model for the future 15 years, respectively. On the contrary, water level for scenario 2 will rebound back to -12 m and -8 m during the future 15 years under the conditions of rapidly growing reinjection. The water level even approaches the initial water level of the reservoir in the 1970s, before exploitation starts. Reinjection for scenario 3 increases relatively slowly, but this is enough to maintain water level at up to -53 m and -50 m for the two types of model, respectively. The water levels of the three scenarios are gathered in Figure 4 for a comparison. The difference of the calculated water level between three tanks closed model and two tanks open model for the three scenarios will get subsequently larger during the future 15 years. This explains that although Xiongxian reservoir has a good recharge (the third tank, aquifers in other nearby geological structures in North China Basin), with large size and permeability, it will also be exhausted gradually and slowly and it is not an infinite resource if no reinjection is applied. It is easy to see that the tendency of the water level for each scenario is to reach a new steady value within one or two decades. This reveals that Jixian reservoir has a rather good recharge and that it behaves more like an open reservoir.

3.3 Geothermal resource assessment with volumetric method

The Xiongxian geothermal system consists of an Upper Tertiary sandstone reservoir and a Jixian system fissured dolomite bedrock reservoir. The assessment area is constrained by the Xiongxian administrative territory. Similarly, applying volumetric method, it is found out that the volume of geothermal fluid stored in the Tertiary and Jixian reservoirs are $18.4 \cdot 10^9$ m^3 and $9.60 \cdot 10^9$ m^3, respectively. The recoverable heat is estimated to be $3.85 \cdot 10^{18}$ J and $2.48 \cdot 10^{18}$ J, respectively. The exploitable volume of geothermal fluid of the two reservoirs are $0.368 \cdot 10^9$ m^3 and $0.192 \cdot 10^9$ m^3, respectively.

4. CONCLUSIONS

1) Modelling of pressure changes observed in geothermal wells in Xianyang reflect an average permeability of around 5 mD. The Xianyang reservoir appears to have fairly good internal permeability but a relatively lower external permeability.

2) A two tank open and a three tank closed lumped parameter models are used to simulate the pressure changes observed in three geothermal wells in Xianyang. Consequently, the two models are used to predict pressure changes for different production scenarios. The pressure predictions by the two models are not significantly different and the predicted pressure curves both decline at a fixed rate. This indicates that the sandstone reservoir in Xianyang responds to production more like a closed reservoir. Besides that the estimated conductance between different model tanks, the estimated permeability of different reservoir parts and the pressure predictions, all point to the conclusion that the Xianyang geothermal system is a closed reservoir with a rather weak recharge.

3) The predictions for well Sanpu2 indicate that the pressure will drop 0.75 bar and 0.66 bar per year for the open and closed models, respectively, if the current production is maintained for the future 15 years. The pressure will drop 0.63 bar and 0.55 bar per year according to the two models, respectively, if 15% reinjection is maintained. In contrast, the pressure is predicted to drop 0.94 bar and 0.83 bar per year, respectively, if production is increased by 25% without any reinjection.

4) It can deduce the four faults, which are believed to act as recharge boundaries of Xiongxian geothermal system, play a role of recharge. The Jixian reservoir is rather promising and is believed to have a large potential for future exploitation, partly because reinjection will be easily applied there. The most important result obtained for this region is the extremely high internal permeability of up to 280 mD, estimated by modelling pressure changes. This is also one of the reasons why reinjection can be so easily applied without any pumping pressure. The external permeability of the geothermal system is estimated to be around 10 - 40 mD.

5) Predictions by lumped parameter models simulating the whole production and response history of the Xiongxian system indicate that water level will approach a new equilibrium at -90 m and -93 m according to the open and closed models, respectively, during the future 15 years at the current production rate, if reinjection is not applied, due to the apparently open boundaries. It is predicted to rebound rapidly to -10 m in a prediction assuming a positive reinjection scenario (reinjection increasing to 85%), according to the two models. Water level predictions for the negative reinjection scenario (reinjection increasing to 50%) indicate that the water level will stabilize at around -50 m.

6) Pressure predictions by the two models for Xiongxian are qualitatively not very different, but the difference from the Xianyang case is that the predicted pressure approaches stable levels instead of going down at a fixed rate. The pressure predictions together with the conductance between different model tanks and the estimated permeability of different reservoir parts, all obviously indicate that the Jixian reservoir in Xiongxian is an open geothermal reservoir.

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