Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

The Influences of Soil Properties on Temperature Field of Saline Aquifer

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Keywords: saline aquifer, properties of the soil, numerical simulation, temperature field

ABSTRACT

The comprehensive application of thermal energy storage technology using superficial underground saline water has become the new direction for the development of groundwater source heat pump. The properties of saline aquifer are the key parameters to affect the energy utilization of groundwater source heat pump. Based on a couple numerical model of groundwater flow and heat transferring in the aquifer, and combined with a project for groundwater source heat pump system in Binhai New Area in Tianjin, a numerical model was developed to simulate the variation of temperature field due to heat and fluid flow with various properties of the soil and also the influence range of temperature field in different saline aquifers under the same running conditions. On this basis, a theoretical analysis was made on the relationship between the soil properties of the saline aquifer and the characteristics of temperature field. The results show that, the influence range of geo-temperature field in saline aquifer changes with the variation of the soil properties under the influences of the underground water flow condition and thermal conductivity system, and the heat transfixion among pumping –injection wells could be avoided or reduced if selecting the proper saline aquifer to inject under the same operation situation.

1. INTRODUCTION

The groundwater source heat pump technology is a high-efficient, energy saving and renewable one introduced to China in the last century. Based on reverse Carnot cycle principle, the energy obtained from the superficial soil and superficial ground water resources with the input of a small quantity high grade power can be made into the hot/cold energy sources for winter/summer, by then the transformation from low grade energy to high grade energy is realized. The abundant low enthalpy superficial geothermal resources are able to be efficiently recovered during its utilization cycle and be reused under rational design and operation.

In recent years, a series of extensive researches have been made upon the utilization of ground thermal resource. In the related studies, the underground aquifer is regarded as energy storage layer to study the change of its inner temperature field. Many research achievements have been gained on groundwater-thermal transfer law, the analysis of heat exchange mechanism of ground aquifer, the flow transfixion problem in aquifers around the injection wells under related energy storage conditions, and the relationship between flow transfixion and heat transfixion (Paksoy H O. et al.,(2000); ZHANG Zhi-hui et al.,(1997); WANG Ming-yu et al., (2004)).

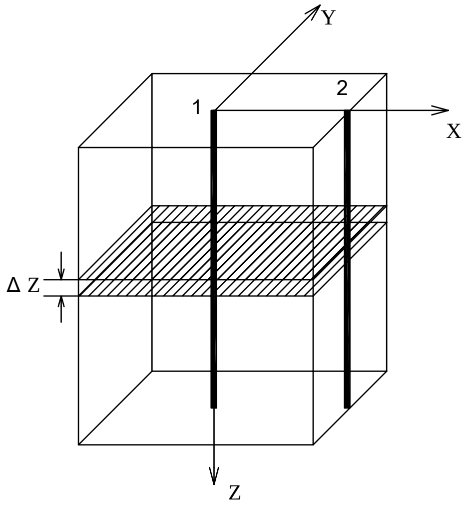
The comprehensive application of ground energy storage requires the water resources to be of great quantity, in shallow depth of burial, with stable water temperature which ensure abundant cold-thermal sources and reduce the cost expenditure and later maintenance. Unfortunately, most of coastal areas in China are in serious shortage of underground freshwater resources, over mining situation and a great depth, which are generally more than 200 meters deep. However, only few of the superficial ground saline water with a depth of about 100 meters are exploited and abundant water resources are left unused. Studies showed that, the coefficient of permeability is larger when the particle diameter of the sand seam of aquifer is larger which makes sure the large quantity water yield per well in one aspect and high injection-pump ratio which makes it easy for the groundwater to inject in another aspect (ZHANG Yuan-dong et al. (2006)) Therefore, the domestic thermal energy storage technology basically chooses the gravel and medium-coarse sand layers of the aquifer. Nevertheless, the porous medium of saline aquifer is mainly consisted of fine sand with a large sand thickness. What's more, as the water quality is complicated, the degree of consolidation of soil body in aquifer is relatively low and the environmental problems generated during the utilization are complex, the research degree of energy storage mechanism is relatively low, which all calls for the comprehensive study of the energy utilization in underground saline aquifer.

A numerical simulation for the temperature field of soil around the pumping wells was made in this paper by adopting professional calculation software. First is the influence that the various properties of the soil imposed on the saline aquifer temperature field under the same operation conditions aiming at a doublet system. On this basis, taking a certain saline aquifer water heat pump system in Binhai New Area in Tianjin as an example, a simulation was done at various soil structure layers on the change conditions of saline aquifer temperature field under cooling mode, from which reliable evidence is provided to determine an proper injection depth, increase the performance of heat pump and avoid the occurrence of heat transfixion.

2. THE PHYSICAL AND MATHEMATICAL MODELS OF THE UNDERGROUND SALINE AQUIFER

2.1 Physical Model

The aquifer soil is divided into n construction layers ΔZ according to the soil difference with the comprehensive consideration of many factors, such as soil properties and water-heat transmission parameters; the pumping and injection wells are divided into n source items according to preset n construction layers. As a result, the former pump and injection wells model is divided into n layers on Z axis, showed in fig 1.



1: Injection well 2: Pumping well

Figure 1 : The physical model of underground saline aquifer

2.2 A Couple Numerical Model of Saline Aquifer Groundwater Flow and Heat Transferring

At present, researchers have already made profound studies on the construction of permeation flow model and heat transportation model of underground aquifer (Hikari Fujii et al. (2007); ZHANG Yuan-dong et al. (2006)). Usually, the water flow conceptual model under energy extraction model of pump-injection system is defined as below: the chosen underground aquifer should be the artesian aquifer with characters of horizontal structure, heterogeneity, anisotropy, and 3-dimensional unsteady flow system. On this premise, the deformation caused by geological structure is mainly on vertical direction but not horizontal, and at the same time, the aquifer porosity is variable while the water density is assumed as constant. In accordance with this model, the groundwater permeation flow model under the pumping-injection operation situation is generally described by the following differential equation:

$$\begin{cases} n\rho_0\beta_p\frac{\partial P}{\partial t}+n\rho_0\beta_\theta\frac{\partial \theta}{\partial t}+\rho\alpha_b\frac{\partial P}{\partial t} \\ =\nabla\cdot\rho\frac{\underline{\underline{K}}}{\mu}(\nabla P+\rho_g)+q\rho^*, x,y,z\in\Omega, t\geq 0 \\ P(x,y,z,t)\big|_{t=0}=P_0(x,y,z), x,y,z\in\Omega \\ P(x,y,z,t)\big|_{\Gamma_1}=P_1(x,y,z,t), x,y,z\in\Gamma_1, t\geq 0 \\ q_{f,n}\big|_{\Gamma_2}=(q_{f,x},q_{f,y},q_{f,z}), x,y,z\in\Gamma_2,\ t\geq 0 \end{cases} \quad (1)$$

In this equation : n : the effective porosity of the aquifer medium; P : fluid pressure (Pa) ; θ : temperature(℃) ; ρ : fluid density (kg/m^3) ; ρ^* : source item density of the fluid (kg/m^3) ; ρ_o : fluid density at the condition of reference pressure p_0 and reference temperature θ_0 (kg/m^3) ; β_p : compressibility coefficient of the fluid (1/ Pa); β_θ : thermal expansion coefficient of the fluid (1/℃) ; α_b : porous compression coefficient (1/ Pa) ; $\underline{\underline{K}}$: permeation tensor of porous medium (m^2); μ : coefficient of dynamic viscosity ($kg/m\cdot s$) ; g : acceleration of gravity (m/s^2); q : source item strength ($m^3/m^3\cdot s$), positive when inflow and negative when outflow; t : time (s); P_0 : the initial pressure distribution of the permeation area (Pa) ; P_1 : the pressure distribution of the known pressure boundary (Pa) ; Ω : underground water permeation region; Γ_1 : pressure boundary ; Γ_2 : impulse boundary ; $q_{I,n}$: underground water impulse of the second class boundary $q_{I,x}, q_{I,y}, q_{I,z}$: the direction component separately.

Supposing the aquifer skeleton has the same temperature with the surrounding flowing water and neglecting the influence of the natural convection, the groundwater heat transfer model can be described by the following differential equations:

$$\begin{cases} n\rho_0\beta_p c_f\theta\frac{\partial P}{\partial t}+n\rho_0\beta_p c_f\theta\frac{\partial \theta}{\partial t}+\rho\alpha_b c_f\theta\frac{\partial P}{\partial t}+n\rho c_f\frac{\partial \theta}{\partial t}- \\ \rho_s c_s T\alpha_b\frac{\partial P}{\partial t}+(1-n)\rho_s c_s\frac{\partial \theta}{\partial t}=\nabla\cdot(nK_f+(1-n)K_s) \\ \times\underline{\underline{I}}\nabla\theta+\nabla\cdot n\underline{\underline{D_H}}\nabla\theta-\nabla\cdot\rho\rho_r v\theta+q\rho^* c_f\theta^* x,y,z\in\Omega, t\geq 0 \\ \theta(x,y,z,t)\big|_{t=0}=\theta_0(x,y,z), x,y,z\in\Omega \\ \theta(x,y,z,t)\big|_{\Gamma_1}=\theta_1(x,y,z,t), x,y,z\in\Gamma_1, t\geq 0 \\ q_{f,n}\big|_{\Gamma_2}=(q_{f,x},q_{f,y},q_{f,z}), x,y,z\in\Gamma_2, t\geq 0 \end{cases} \quad (2)$$

In Eq.(2) : $\underline{\underline{I}}$:3 order unit matrix; $\underline{\underline{D_H}}$:thermal power dispersion coefficient tensor (W/ m·℃) ; c_s : specific heat of porous medium (J / kg ·℃) ; c_f : specific heat of the fluid (J / kg ·℃) ; ρ_s : pore medium density(kg/m^3) ; K_f : thermal conductivity efficiency of the fluid (W/ m·℃) ; K_S : thermal conductivity efficiency of porous medium ; θ_0 : the initial temperature distribution of the permeation area ; θ_1 : the temperature distribution of the known temperature boundary ; Γ_1 : known temperature boundary ; Γ_2 : heat flow boundary ; $q_{f.n}$: the boundary of the heat flow (m^3) ; $q_{f,x}, q_{f,x}, q_{f,z}$: component at x , y, z directions respectively

2.3 The Definite Conditions of a Couple Numerical Model of Saline Aquifer Groundwater Flow and Heat Transferring

Applied the above model to a certain project in the Binhai New Area, the analyses were made on the influence of the properties of the soil imposed on the saline aquifer energy storage. In order to eliminate the interaction among the well groups, simplify the complex degree of the model, and combine with the geological and hydro geologic conditions of this area, some statistics are set in the simulation calculation as: the target area is a 300m×300m square one, the production well is a doublet well system with 0.32 diameter and 150 meters distance between each other, which means that, there are a pumping well and a injection well with the same structure; the properties of the soil are supposed to be same and isotropy in micro element body ΔZ; the initial temperature is 289.5 K, pumping rate is 20 m^3/h, the injection temperature is 294.5K, the injection rate is 17 m^3/h which is 85% of the pumping rate.

The operation mode of this water source heat pump is supposed to be operated under a continuous cooling mode for 100-day, i.e. 1848h, the unit is runned all day around and the temperature difference is thought to be constant between the reinjection and pumping waters when the heat transfixion started.

3 ANALYSIS OF THE SIMULATION RESULT

3.1 The Temperature Field Distribution of Saline Aquifer Surrounding the Injection Well

Under the little effect of the natural convection field and influence of forced conversion driven by pump; the energy storage water injected into the aquifer is not distributed averagely around with the centerline as the circle center but an obvious shift instead. The energy storage water mass is elongated along the direction of the new permeation field formed after the pumping and will be flat with the shape of a pear when the pumping reaching a certain degree. With the constructed model above, after 100 days operation, the simulation is made under the condition that the specific heat of the soil property of saline aquifer is 0.7kJ/kg · K , the thermal conductivity is 1.5 W/m · ℃, the porosity is 40%, and the effective size of the soil particle is 0.05mm. The result is showed in fig 2. The temperature field of saline aquifer has a biggest expansion among the X axis influenced by the pressure of pumping and injection wells. Therefore, in order to describe the influence range of the temperature field precisely, an influence range by injection well is defined as the range for at least 0.5℃ temperature raise in saline aquifer caused by the injection, and thermal effects radius *R* is defined as the distance between the farthest coordinate point of the influence range and the center of the injection well in this paper.

3.2 The Influence of Soil Properties on Thermal Effects Radius of Saline Aquifer

3.2.1 The Specific Heat c of Saline Aquifer Soil

As showed in table 1, with the same operation conditions of groundwater source heat pump system and other soil properties unchanged, the simulation is done on the change of the thermal effects radius according to the change of the heat pump operation situation with different *c* values.

Table 1 The Parameters of Soil Properties

The Parameters of Soil Properties	Ⅰ	Ⅱ	Ⅲ
Specific heat: *c* kJ/kg · ℃	0.7	1.4	2.2
Thermal conductivity: *K* W/m · ℃		1.5	
Porosity: *n* %		37	
Effective size: D_p mm		0.05	

As showed in Fig 3, the thermal effects radius becomes smaller as *c* becomes larger. The reason is that *c* is the parameter to represent the thermal storage capacity of the soil, the larger c is, the larger is the heat quantity absorbed per soil unit volume, and the smaller is the influence range of the injection well under the same operation condition.

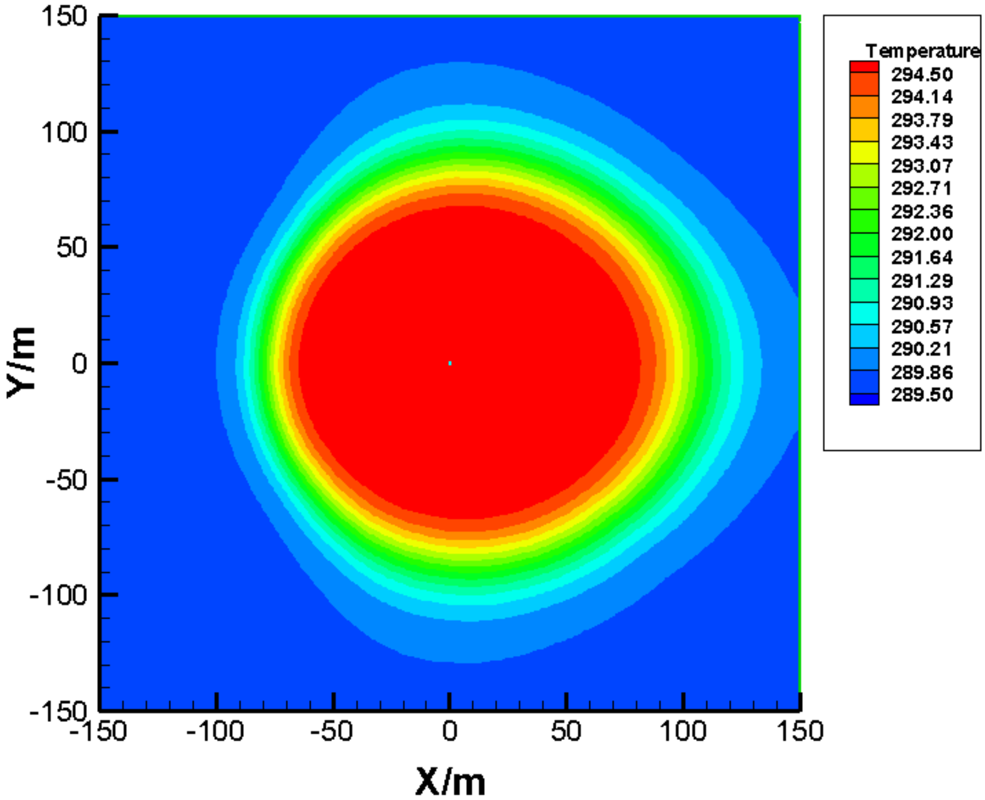


Figure 2: Temperature field in saline aquifer surrounding the reinjection well

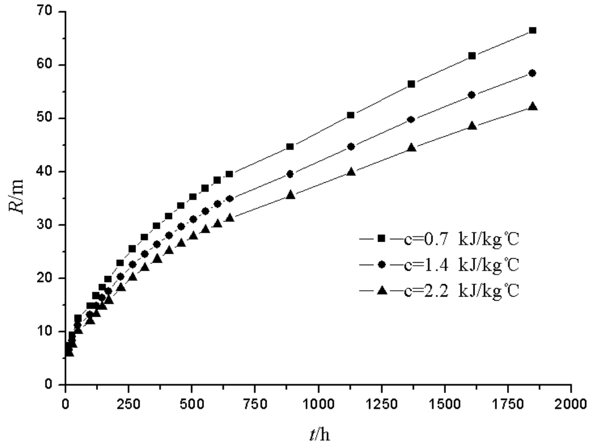


Figure 3 : The influence of specific heat on thermal effects radius in different time

3.2.2 Thermal Conductivity *K* of Saline Aquifer Soil

K is the thermal conductivity of the saline aquifer and the key parameter to determine the thermal properties. In this paper, the value of the thermal conductivity is changed to analyze the influence on the thermal effects radius.

Table 2 The Parameters of Soil Properties

The Parameters of Soil Properties	I	II	III
Specific heat: c kJ/kg·℃		1.4	
Thermal conductivity: K W/m·℃	0.7	1.5	2.5
Porosity: n %		37	
Effective size: D_p mm		0.05	

As showed in Fig 4, the result of the simulation calculation is that, the thermal effects radius is expanded slightly with the increase of K in the beginning of the injection. One important reason is that, in water source heat pump system, as the heat conduction process of saline aquifer is convective heat transfer caused by the enforce convection during the injection process, the heat conduction amount of underground water and porous medium in saline aquifer during the heat conduction process can be neglected compared to the convective heat transfer process. Therefore, a small influence on thermal effects radius is shown changing heat conductivity, *K*.

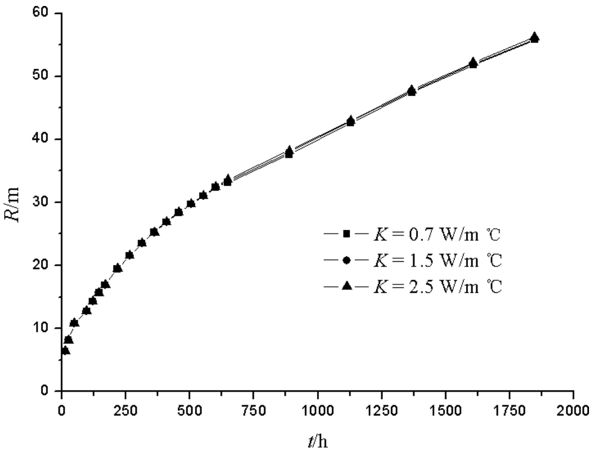


Figure 4 : The Influence of heat conductivity on thermal effects radius in different time

3.2.3 The Porosity *n* of Saline Aquifer Soil

The soil porosity is the ratio of pore space (volume sum occupied by liquid phase and gaseous phase) and the whole soil volume. Usually, the soil porosity is between 0.2 and 0.6. As showed in table 3, the changes of thermal effects radius under different conditions are calculated by changing values of *n*.

Table 3 The Parameters of Soil Properties

The Parameters of Soil Properties	I	II	III
Specific heat: c kJ/kg·℃		1.4	
Thermal conductivity: K W/m·℃		1.5	
Porosity: n %	48	37	20
Effective size: D_p mm		0.05	

As showed in Fig 5, the thermal effects radius becomes larger as the porosity becomes larger. According to Darcy law, the seepage velocity of groundwater in soil is proportional to the size of porosity (Sijnhild Gehlin, (2002)). Simultaneously, the enforce heat convection effect is strengthened obviously with the increase of permeation speed which makes the heat transfixion occur more easily.

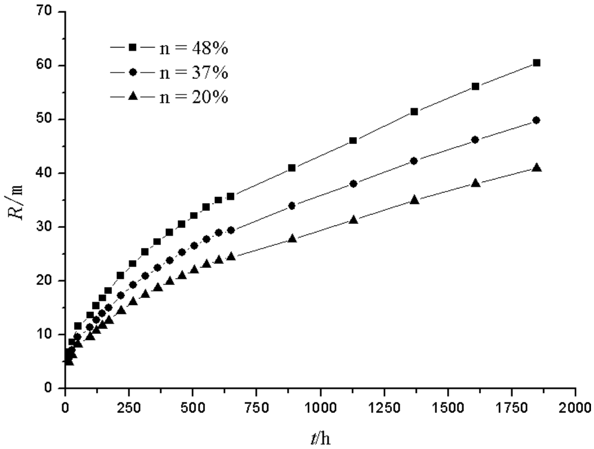


Figure 5 : The influence of porosity on thermal effects radius in different time

3.2.4 The Effective Size D_p of Saline Aquifer Soil

The texture and structure of the soil are the basic physical characters. The texture means the main diameters of the solid particles or the range of them which compose the soil, and the main diameters are classified as gravel, sand particle, silt particle, and clay particle generally. As the soil is a porous medium, the effective size of the solid particles is commonly selected as the physical properties to study its characteristics. Table 4 shows the thermal effects radius got with the changing of effective size (particle diameter) D_p.

Table 4 The parameters of soil properties

The parameters of soil properties	I	II	III
Specific heat: c kJ/kg·K		1.4	
Thermal conductivity: K W/m·℃		1.5	
Porosity: n %		37	
Effective size: D_p mm	0.01	0.05	0.1

As shown in Fig 6, the influence range of thermal diffusion caused by water injecting to injection well expands as D_p

becomes larger. According to Darcy law, the permeability coefficient becomes larger when the effective size increases and moreover, there is a decrease in the viscosity resistance and inertia resistance of the permeation flow of groundwater according to Ergun formula. Therefore, as D_p increases, the velocity of ground water permeation raises, heat transfer capability strengthens and the thermal effects radius increases.

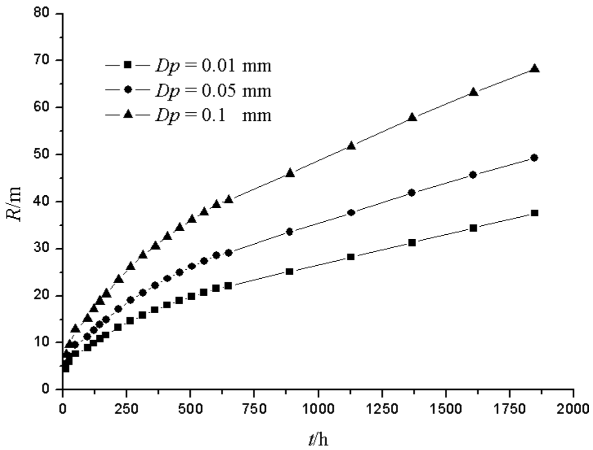
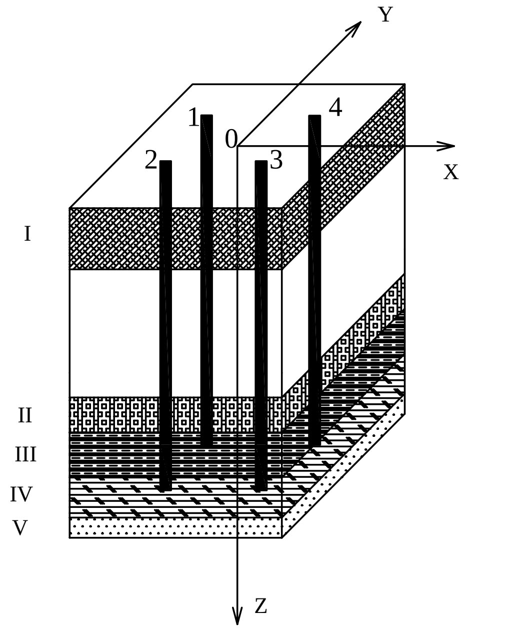


Figure 6: The influence of effective size on thermal effects radius in different time

4 THE CHANGE OF TEMPERATURE FIELD IN DIFFERENT SALINE AQUIFER SOIL

The aquifer usually consists of different soils, such as sand clay, clay soil, sand and gravel and so on. As the physical parameters of different soil vary, the variation of properties of soil should be considered when analyzing their influences on the heat storage capacity of saline aquifer. This paper adopts the mathematical model in 2.2 to analyze the certain groundwater heat pump system in Binhai New Area in Tianjin.

This groundwater source heat pump system adopts three pumping wells and four injection wells with a diameter of 0.32m and a 50m distance between each injection well between each other. The depth of the well is 60m, and the injection part is from 40 m to 60 m under the well. According to the result of the field survey, the saline aquifer in injection area is divided into four layers in accordance with its different soil, as shown in Fig 7 and table 5. The parameter of the soil properties of every layer is supposed to be same and isotropy. In the model, the target area is 300m× 300m, and the three pumping wells are distributed averagely at 150 meters along the X axis. The operation mode of the water source heat pump is in the single summer with a continuous cooling mode for 120-days, i.e. 2424h the unit is runned all day around and the temperature difference is thought to be stable between the injection and pumping waters when the heat transfixion occurs. The initial temperature of groundwater is 289.5K, the pumping rate is $20m^3/h$, the injection temperature is 294.5K, and the injection rate is $15m^3/h$.



I: confining stratum II：Clay Soil III：Sand Clay
IV：Sand and Clay V：Sand and Gravel

Figure 7: Soil Structure Diagram of Saline Aquifer

The simulation show in Fig. 8 that, the thermal effects radius of sand clay is the largest; the influence range of the temperature field has already exceeded 150m to be close to the pumping well after 1345 hours operation, in other words, the heat transfixion occurs. After 2065 hours' operation, the heat transfixion also occurs in sand and gravel layer. But for clay soil and sand and clay, the influence ranges of temperature field are 77.8m and 129.9m separately at the end of the cold supply period which is far behind the former two.

The main reason is that, for the pumping and injection wells with the same structure and operation conditions, the pump amount and injection amount of every saline aquifer layer are allocated according to coefficient of hydraulic conductivity which make ground hydraulic gradient the same. Because of the larger effective sizes over the ones of than the other two. In the heat transferring process of ground saline aquifer, convection is the major influence factor. It is the difference in clay soil and sand and clay, sand clay and sand and gravel gain a higher permeability and seepage velocity permeation speed in various saline aquifers that causes the different influence ranges of heat transfer. Secondly, as the specific heats of clay soil and sand and clay are relatively high, the heat storage capacities are large, which reduce the influence range of temperature field of injection wells.

Table 5 The Parameters of Soil Properties

Layer No.	Soil Name	Heat Conductivity K W/m·℃	Specific Heat c kJ/kg·℃	Porosity: n %	Effective size: D_p mm
□	Clay Soil	1.1	2.2	46.9	<0.002
□	Sand Clay	1.9	1.48	37	0.1—0.5
□	Sand and Clay	1.2	2.0	20	0.05—0.15
□	Sand and Gravel	3.0	1.43	10	0.5—2.0

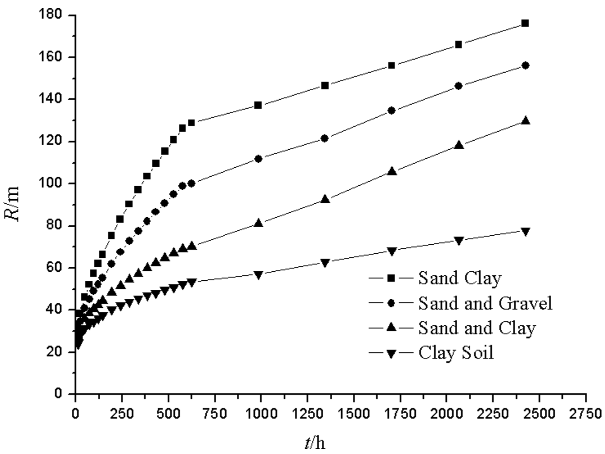


Figure 8 : The influence of saline aquifer soil on thermal effects radius in different time

5 CONCLUSION

Based on a couple numerical model of groundwater flow and heat transfer of aquifer, adopting the profession calculation software, and combined with a project of groundwater source heat pump system in Binhai New Area in Tianjin, a numerical model is developed to quantitatively simulate the distribution of temperature field and the changes according to the operation time, which provides a definite reference for the design of groundwater heat pump system which uses the saline aquifer as the cold and heat sources.

1. The influences of parameters of soil properties on thermal effects radius: under given operation situation, the thermal effects radius is smaller as the specific heat c becomes larger with a maximum 14.31m difference at the end of the cold supply season. The thermal effects radius expands if porosity of saline aquifer soil n and effective size D_p increase which lead to a maximum 19.51m and 30.64m differences at the end of the cooling season. As convective heat transfer takes place in groundwater heat transfer, the thermal effects radius changes slightly if the heat conductivity of soil is changed, which has a maximum 0.46m difference because of the effect of *K* at the end of cooling season.

2. According to the actual project, the simulation under the cooling operation condition based on groundwater heat pump system shows that, the thermal effects radius of clay soil, sand and clay, sand clay and sand and gravel are 176.2m, 156.2m, 129.9m, and 77.9m respectively at the end of cooling season. Among which, the heat transfixion in sand clay takes 1345 hours' operation and the sand and gravel layer takes 2065 hours.

ACKNOWLEDGEMENT

Supported by The Comprehensive Research and Application of Thermal Energy Storage Technology Using Superficial Underground Saline Water in Binhai New Area in Tianjin Project (Grant No. 08ZCGYSF02400)

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