Simulation Study of Heat Transportation in an Aquifer about Well-water-source Heat Pump

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Abstract: The study of groundwater reinjection, pumping and heat transportation in an aquifer plays an important theoretical role in ensuring the stability of deep-well water reinjection and pumping as well as smooth reinjection. Based on the related conception of underground hydrogeology and the rationale of seepage flow mechanics, a geologic conceptual model of doublet reinjection and a seepage flow model of heat transportation are proposed in this paper. The temperature distribution in the temperature field was obtained by a coupled method of the heat transportation equation and groundwater seepage flow equation fitting for the seepage-affected section. The temperature changes in aquifer and heat storage efficiency are analyzed under different working conditions. All the work referenced above provided references for the popularization and evaluation of well-water source heat pump.

Key words: Deep-well Water-source Heat Pump, Aquifer Thermal Energy Storage System, doublet reinjection ，heat transportation model

1. INTRODUCTION

The aquifer thermal energy storage(ATES) is an unconventional technique of energy-saving. It makes the use of the underground water storage structure such as underground rock hole, cranny and solution cavity, as well as characteristics that the water with low velocity of flow and small change of temperature in aquifer. Tube wells are used to injecte cold or warm water to the aquifer. For its own pressure, the injected water can push original groundwater away and stored in the aquifer around wells. This technique can supply cold or heat at different time. The energy is released and recruited by the way of pumping cool water in summer while injecting warm water ,and pumping warm water in winter while injecting cold water . The alternation of pumping and injection is virtually the alternation of the releasing and recruiting of heat/cold quantity. At present, there is few study of heat transportation in the scope of well-water source heat pump technique. Based on theories of groundwater flowing and related heat&mass transportation, the characteristic of heat transportation in aquifer is researched by the way of theoretical calculation and simulation analysis about the temperature field of a pair of wells in confined aquifer. All the work referred above provided theoretic judgement to the popularization and evaluation of well-water source heat pump.

2. MATHEMATICAL MODEL OF HEAT TRANSPORTATION IN AQUIFER

It is a very complicated problem of the heat transportation caused by temperature change in porous medium.The following is tentative for simplified calculation:

1) The convection heat is transported by liquid phase medium;
2) The conduction heat is transported by solid phase medium and liquid phase medium;
3) The heat dispersion caused by transportation in liquid phase is analogous to the hydrodynamic mass transportation;
4) The medium of solid phase is undeformed in the course of heat transportation; meanwhile, the water density is unchanged with the variable pressure.

5) The thermodynamic balance between water and the porous framework in aquifer is considered an instantaneous process.
6) The porous framework has the same temperature as the ambient flowing water, ignoring the heat transportation between them.
7) Based on the energy conservation law, the governing heat transportation equation in unsteady state condition[1],

$$C\frac{\partial T}{\partial \tau} = div(\lambda \cdot gradT) - div(C_w \cdot T \cdot V) \quad (1)$$

Assume that the porous medium framework being undeformable and groundwater being incompressible homogeneous liquid , we have

$$div(V) = 0 \quad (2)$$

So the heat transportation equation for aquifer is:

$$C\frac{\partial T}{\partial \tau} = div\ (\lambda \cdot gradT) - C_w \cdot V \cdot gradT \quad (3)$$

The boundary condition and initial condition are the following, respectively:

$$T(x,y,z,\tau)\big|_{\Gamma} = \psi\ (x,\ y,\ z) \quad (x,y,z \in \Gamma), \tau > 0 \quad (4)$$

$$T\ (x,\ y,\ z,0) = T_0(x,\ y,\ z) \quad (x,y,z \in \Omega) \quad (5)$$

Where :

T—the temperature of the aquifer ,℃;

τ—the time cost for heat transportation,S;

C, C_W —the thermal capacity of the porous medium and water, respectively，J/m3•℃;

λ—the thermodynamic dispersion coefficient of the porous medium,W/m•℃;

V—the seepage velocity vector of aquifer, m/s;

T_0—the initial underground temperature field, ℃;

Ω—the area for calculation;

Γ—the boundary of the area for calculation .

The mathematical model for three-dimensional unsteady flow in confined aquifer is the following[2]:

$$\frac{\partial H}{\partial \tau} = \frac{1}{s}div(K \cdot gradH) + \frac{W}{s} \quad (6)$$

The boundary condition and initial condition are the following, respectively:

$$\left.\frac{\partial H(x,y,z,\tau)}{\partial n}\right|_{\Gamma} = 0 \quad (x,\ y,Z \in \Gamma), \tau > 0 \quad (7)$$

$$H(x,\ y,\ z,0) = H_0(x,\ y,\ z) \quad (x,\ y,Z \in \Omega) \quad (8)$$

Where :

H—the water pressure in aquifer m;

K—permeability coefficient of aquifer,m/d;

s—flexible water-storage coefficient, $1/m$;

W—pumping amount of unit volume，m^3/d;

H_0—the initial water pressure in aquifer ,m.

The heat transportation equation and water flow equation are coupled by Darcy Law:

$$\overline{V} = -K \cdot gradH \quad (9)$$

The heat transportation model equation is composed of Eq.(1),Eq.(6)and Eq.(9). The process of heat transportation, which includes the transportation of water and heat, has relations with groundwater and its dependent medium. The temperature and flow velocity in the same medium are coupled.

3. CALCULATION ANALYSIS OF A CASE

This paper chose a project of ground water heat pump in suburb of northeastern Beijing. The concrete geological condition from Reference (3).

3.1 The Physical Model Establishment of Groundwater Dynamics :

Based on the actual geological condition, the simplified geological model and physical model of production well are defined, as respectively sketched in Fig. 1 (a)and 1 (b).As shown in Fig.1,the well is drilled to the bottom of the confined aquifer, and the water level in the well is lower than the roof of the confined aquifer. Hence, the well is called the confined- phreatic well.

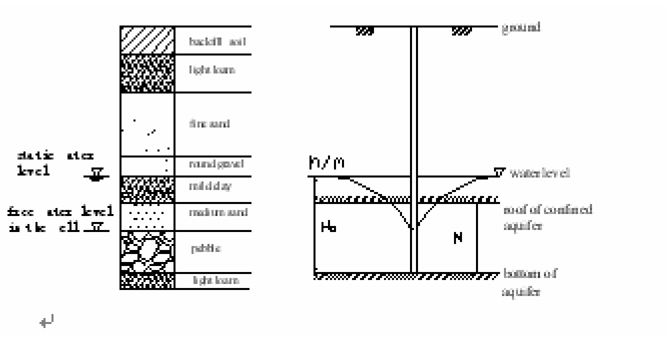

Fig. 1 A geologic model of the aquifer

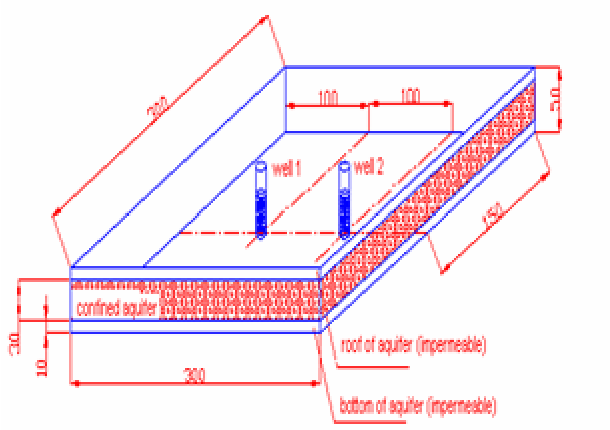

Fig. 2 Calculation model

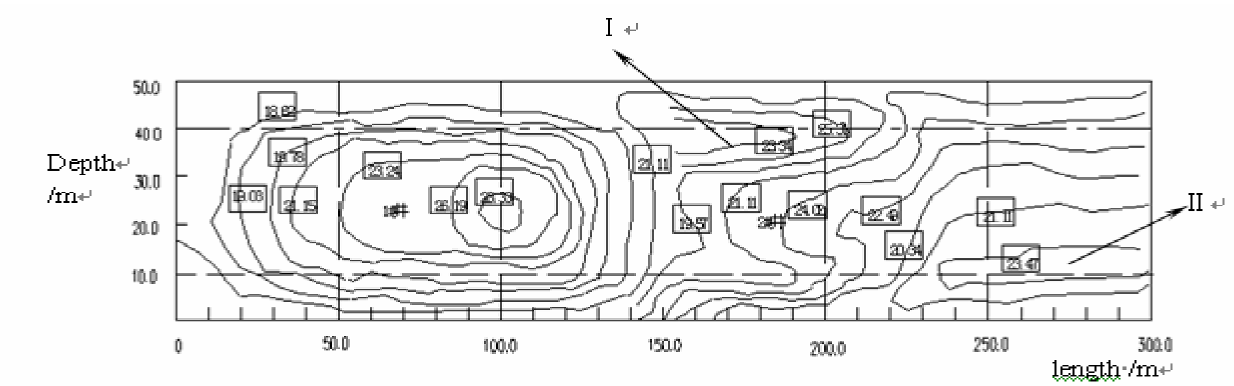

Fig. 3 A water temperature vertical profile in summer （℃）

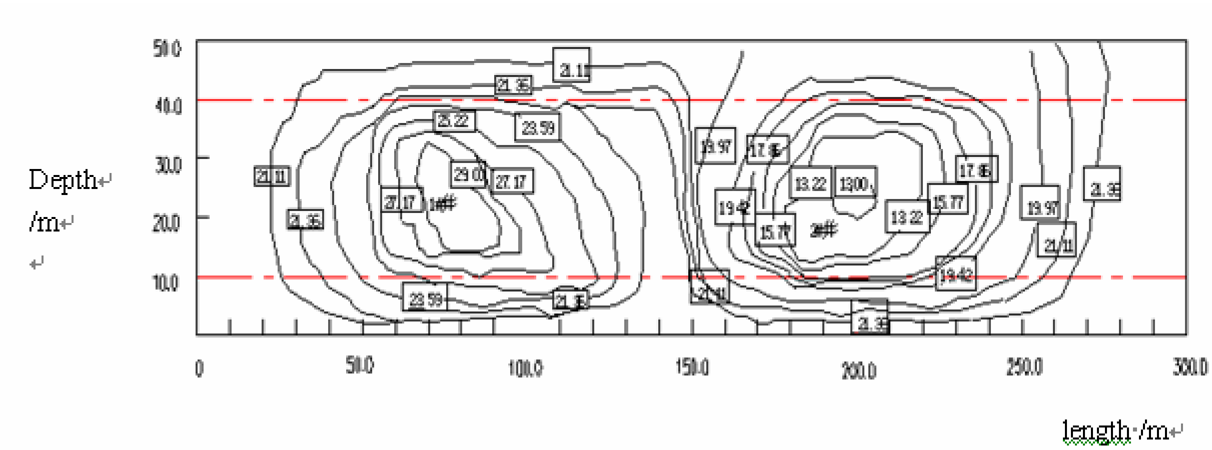

Fig.4 A water temperature vertical profile in transition season （℃）

Tab.1.The mean values of the model parameter for heat transportation in aquifer

stratum	thermal capacity （J/m^3•℃）	thermodynamic dispersion coefficient（W/m•℃）	permeability coefficient （m/d）
roof of the aquifer	2.51×10^6	1.62	70
aquifer	3.02×10^6	18.40	150
bottom of the aquifer	2.09×10^6	2.08	50

3.2 The Value of Parameters for Calculation

Choose a confined aquifer(with an area of 300m×300m×50m) as the calculation area. The total depth of the aquifer is 50m. Between the roof and bottom of the aquifer, which are considered to be impermeable stratums and of 10m thickness, respectively, is the confined aquifer of 30m thickness. In the calculation area, the numbers of production well and injection well are respectively one. The interval between the two wells is 100m and diameters of them are all 500mm.The production well is considered to be confined- phreatic well. The sketch map is Fig.2, and thermal parameters are shown in Tab.1.

The water specific heat C is 4.176×10^6J/m^3•℃. The flexible water-storage coefficient s of the aquifer is 0.18 per meter. The rate of injection is 200t/h(4.8×10^3m^3/d),while the pumping rate is 80% of the injection rate. The depth of ground water is 24m,the water temperature pumped out is 13～15℃.The ambient initial temperature of the aquifer is 17℃.In summer, the well NO.1 is injection well for energy storage, while NO.2 is production well. The exhaust water of overground water loop system for injection is 29℃.The operation time for cold is 112 days, from May 30 to Sep.20. In winter, the well NO.1 is production well, while NO.2 is injection well for energy storage. The exhaust water of overground water loop system for injection is 8℃. The operation time for heating is 191 days, from Oct..25 to Apr.10 (the next year).The other time of the year is transition season when the wells stop working.

3.3 The Implementation Procedure Of Numerical Simulation

The HST3D groundwater computer program was selected to study the Water-Thermal Model, which is composed of Eqs.（1），（6），（9）, corresponding initial conditions and boundary conditions. Three –Dimensional flow Heat and Solute Transport Model is called HST3D for short, it is an open computer program developed by United States Geological Survey （USGS）in later 1980s for groundwater study, such as the simulation of flow, heat transfer and mass transfer in aquifer .

According to the longitudinal geological condition shown in Fig.1,in this paper, the calculation model has been divided into three layers , 9000 cells(300×30) ,one cell per meter. The “Well” subprogram was firstly called for the seepage field solution — values of water pressures and velocity within the research zone. Then “Thermal” subprogram was called for coupled calculation. With advantages of high accuracy, high convergence pace and stability without any condition [2] , the Douglas-Brain ADT finite difference method has been selected for equation discretization. The time step is 2h and the convergence criterion is injection flux residual ≤5%.

3.4 Result Analysis

Fig.3 is the water temperature vertical profile in the middle of the aquifer(y=150m),under the condition that the system operating for 30days in summer working condition.

Isotherms bending to right clearly reflect the state of pumping. In the operating duration, water-carrying is the main type of heat transportation for higher seepage velocity. In the beginning of pumping, the water of higher temperature mainly comes from well NO.2(the production well);the temperature decreases gradually with the increase of total pumping amount.

Thermal diffusion of lower velocity is the main type of heat transportation in upper and bottom impermeable stratums, so compared with confined aquifer, there is respectively a high-temperature zone in upper and bottom impermeable stratums(as Ⅰ and Ⅱshown in Fig.3).

In winter operation mode, the function of the two wells is different from summer mode, however, the water temperature vertical profile is similar to summer mode, so it can be omitted.

Fig.4 is the water temperature vertical profile in the middle of the aquifer(y=150m),under the condition that the system stoped operating for 30days after summer mode. As shown in Fig.4, the temperature vertical profile of the warm and cool water body is diffuse distribution. The reason is : higher temperature water with lower density at the bottom of the aquifer moves to the top of the aquifer and mixes with the lower temperature water here, so the temperature of the whole body of water trends to be the same .The axes of the wells are centers of the horizontally laminated temperature distribution .The frontal of the body of warm water extend gradually to the range of production well(the sigh is water isotherm of 21℃), it is the existence of thermal connectivity. In winter mode, the temperature of water pumped from well NO.1 is higher than the initial temperature of the aquifer, which indicates a good temperature conservation capacity of the aquifer, so the energy of injection water can be stored for the purpose of thermal energy storage.

3.5 The Efficiency Analysis of Thermal Energy Storage of the Confined Aquifer

The water with temperatureT_1 (higher than the initial temperature T_0 of aquifer) injected to the thermal energy storage aquifer will lose energy for thermal diffusion; the temperature T_P of pumping water will decrease for the same reason. The efficiency of thermal energy storage ε is defined as: the ratio of the extracted energy and the stored energy ,in the condition that the pumping amount equals to the injection [4] ;that is:

$$\varepsilon = \frac{\int_{t_1+t_s}^{t_1+t_s+t_p} (C_w T_p - C_w T_0) Q_p dt}{\int_0^{t_1} (C_w T_1 - C_w T_0) Q_1 dt} \qquad (10)$$

Where:

t_1, t_s, t_p —the working durations of injection, stop and pumping, respectively, in day.

Q_p, Q_i — the time rates of pumping and injection, respectively, in tones per day(t/d) .

Based on the water temperature vertical profile referred above, the temperature distribution in water bodies of production well and injection well can be obtained under different operation conditions. Furthermore, the energy storage efficiency can be obtained by formula (10). Based on the water temperature vertical profile shown in Fig3, select the average values of t_p and t_1 are 15℃ and 23℃, the pumping rates and injection rate are 160t/d and 200t/d, respectively, then obtain the corresponding ε is 54% .Actually, different ε can be obtained with different water amount and water temperature in every operation condition, so ε is a quantity varying with the operation conditions of the overground system. Meanwhile, in order to meet the water requirement of the water circuit system, the general standard of aquifer as water source is high porous ratio and high permeability. But in the view of heat transportation, the higher the thermal diffusivity of the aquifer, the easier the stored thermal energy diffuses to the upper and bottom impermeable stratums; the high permeability of the roof and bottom of the aquifer, will lead to relative high heat loss for the reason of water-carrying and low efficiency of aquifer thermal energy storage. So on the premise of ensuring sufficient water supply, the discussion of geological condition, especially the influence of conditions of the upper and bottom impermeable stratums on the efficiency of aquifer thermal energy storage, is a worthy topic for further study.

4. CONCLUSION

The well efficiency estimate for Aquifer Thermal Energy Storage (ATES) is one of the important indexes about the economic performance of well water-source heat pump. The well energy storage efficiency ε has been theoretically calculated. The conclusions are the following:

The change trends of isotherms in the temperature field can reflect the aquifer temperature field changing with amounts of pumping and injection, and the injection temperature. The rule of heat transportation can be used to study the characteristic of temperature change of the pumping water, which gives us a clearer cognition of the efficiency of aquifer thermal energy storage and its characteristic. Therefore, the study of heat transportation in aquifer plays a theoretical part in further use and appraisement of aquifer thermal energy storage.

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