ESL-IC-06-11-299

Optimal Well-Group Distribution of a Groundwater Source Heat Pump System[1]

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Abstract: It is critical to determine how the well group arranges for application of the GWSHP system. Based on the fact that water movement is the most important factor influencing heat transfer in an aquifer, this paper presents a two-step analysis method and analyzes the inter-well thermal transfixion method as follows. First, we forecast the least influence radius through calculating the thermal diffusion function of aquifer. Then, we perform an analysis on the inter-well thermal transfixion, using the streamline analysis method and doing a quantitative analysis of the effects that inter-well distance and flux have on it. We discuss the well group arrangement and puts forward optimal scheme by means of the thermal diffusion and streamline simulation.

Key words: water/heat movement; well group arrangement; thermal transfixion; optimization

1 FOREWORD

The green technology GWSHP system is good for sustainable development. It makes use of groundwater as cold source or heat source, and its COP is higher than other air conditioning system, so it has higher environmental protection and economic value. Well group is an important part of GWSHP system, its operation performance is the linchpin which success or failure of the whole system depends on. At present, in the process of the domestic well group design and construction of this kind project, the criterion of system scheme feasibility are the singer well water flow rate and the achievement of the favorable recharge. But in the process of well group distribution feasibility analysis and design, several problems must be taken into account:

(1) The local aquifer thermal energy storing and transfer process

While utilizing the GWSHP system, it needs to know the building cubage rate limitation that the system could burden. When the building annual cooling/heating load is not regularity, what perennial influence effect that the system makes on aquifer water temperature, whether brings about the aquifer
"background temperature" reduction or increase year by year and leads to the system operation fail. How to constitute the relative reply strategy?

(2) The avoidance of "thermal transfixion" effect

Because of the difference between recharge water temperature and initial aquifer water temperature, under the influence of conduction and convection, recharge water "temperature front" will induce the pumping well vicinity inlet water temperature increase or reduction, the phenomena always be called as "thermal transfixion"[1]. How to ascertain the fitting well spacing and the well group distribution to avoid the "thermal transfixion" effect are the regardful problem to designer.

(3) The effect of ground unit and ductwork form

1 Supported by the Scientific Research Project of Hunan Provincial Education Department(04C537).

and operation mode

While utilizing the "small flux, large temperature difference" system function mode, it can achieve the maximum use of aquifer thermal energy storage and reduces the use of underground water resource. Under the two operation situation of "small flux, large temperature difference" and "large flux, small temperature difference", the temperature field variation on aquifer and the induced discrepancy of well group distribution, are the regardful problem to designer.

Water/heat movement on aquifer restrict the GWSHP development. At present, the problem is being studied in kinds of science, such as Environmental Science, HVAC, Geological Sciences and so on. The behavior of natural convection and its impact on groundwater thermal transport are studied by Zhang Zhihui[2]. Wang Jingguo[3] simulates the groundwater thermal transport through using the BEM-FAM couple method. Liggett and Liu use Laplace transformation and BEM to calculate the unstable state groundwater flow equation[4]. Prickett solves the water movement problem in aquifer through rondom walk method[5] and S. Chevalier applies this method solve the couple equation about the groundwater flow equation and flow transfer equation[6] . Sudicky adoptes LTGT (Laplace transformation and Galerkin technique) simulate the transfer of contamination enter aquifer through the fracture [7].XUE Yuqun uses the characteristic finite element method to solve the advection-diffusion equation about seawater infall[8].

There are three heat transfer ways in aquifer: (1) heat conduct of solid; (2) heat conduct of liquid; (3) heat convection of liquid. Heat convection of liquid is the primary factor for heat transfer, based on this, the paper puts forward two steps analysis method to analyze the Water/heat movement in aquifer. Firstly, it forecast the least influence radius through calculating the thermal diffusion function of aquifer; secondly, based on the trace and streamline superpose in steady state and incompressible zone, it brings forward streamline analysis method and ascertain the inter-well thermal transfixion.

It simulates the summer condition of three wells system at north of china, the groundwater temperature is 15℃, observes the temperature profile and streamline profile after consecutive recharge sixty days. Tab. 1 is the thermodynamic performance of aquifer.

Tab. 1 The soil hydraulic and thermal parameter

Parameter	Aquifer	Aquiclude	Unit
Permeability	5.3×10^{-11}	1×10^{-12}	m^2
Porosity	0.3	0.25	
Solid framework Compressibility coefficient	4.6×10^{-4}	4.6×10^{-4}	Pa^{-1}
Solid framework Specific heat	696	696	J/(kg·℃)
Solid framework Thermal conductivity coefficient	2600	2600	kg/m^3
Vertical dispersion rate	4	0	m
Transverse dispersion rate	1	0	m

2 THE CONFIRM OF LEAST INFLUENCE RADIUS

The temperature field simulation is accomplished by two steps. Firstly, adopting the thermal balance method, it calculates the eventually temperature on each influence radius after recharge and selects several representative temperature. Secondly, it substitutes the temperature in thermal diffusion equation by the representative temperature and introduces MATLAB to calculate temperature distribution curve. It simulates the least influence radius under the three temperature difference, 5 , 8 , 10 .

2.1 The Confirm of Thermal Transfixion Initial Temperature in Aquifer

Adopting thermal balance method, the simulation finds out the rough thermal influence field under recharge condition, ascertains temperature under each influence radius.

Hereinafter, it is the concrete analysis.

After injecting certain quantity (G/t) water, radius of the space that injecting water occupies in aquifer is:

$$R = \sqrt{\frac{G}{\pi d \eta}} \tag{2-1}$$

Where d is the aquifer thickness, η is the sand grain porosity; If it is identical quantity injection every time, while the water stratum forth advance, the square difference of each two stratum radius keeps equally. When the first G ton (t) water is injected in, it will occupy sand grain pore in aquifer that around well by radius of R_1 and drives original underground water that occupy the pore out of the circle. In this way, the heat exchange will happen between injecting t water and sand grain (original underground water temperature is t_0). It will attain balance temperature t_{11} of corresponding radius R_1:

$$G \times \rho_w \times C_w \times (t_0 - t_{11}) = \pi \times R^2 \times d \times (1-\eta) \times \rho_s \times C_s \times (t_{11} - t_a) \tag{2-2}$$

Where ρ_w is the water density, C_w is the water specific heat, t_{11} is the balance temperature, ρ_s is the sand grain density, C_s is the sand grain specific heat

When the second G ton (t_0) water is injected in, G ton (t_{11}) water that has been injected in at the first time is driven out of the circle that takes well as center and the radius is R_2. Following the above analysis:

$$R_2^2 - R_1^2 = \text{constant} \tag{2-3}$$

Here, the heat exchange is happening between the just injecting t_0 cold water and t_{11} sand grain. It will attain new balance temperature t_{21} of corresponding radius R_1. Moreover, the heat exchange between t_{11} water and t_a sand grain, will attain another balance temperature t_{22} of corresponding radius R_2. The rest may be deduced by analogy, until all the demand water have been injected in. The draw out condition is opposite. It can compile the temperature of each radius R_i in the last time, the concrete framework is Fig.1. After calculation, it can pick out several typical temperatures as initial temperature of thermal diffusion calculation. It shows in Tab.2.

2.2 The Physical and Mathematics Model of Thermal Diffusion Simulation

1) The physical model

Considering the alternation of draw out well and recharge well, while simulating single well temperature field, it takes draw out well 2D MATLAB model for the simulation. It is 120m in length direction, while in height direction, taking an aquifer and an aquifuge into account, is 60m. For the ∇T is 8 and 10 , it is also 60m in length direction. The model shows in Fig.2. Where, the R_1 is aquifer, 30m in height, 100m in length; the R_2 is aquifuge, 30m in height, 100m in length; the R_3 is a single well, the well mouth locates in the center of aquifer, 45m in length, well diameter is 400mm. The parameter is show in Tab.1.groundwater

Tab. 2 Initial temperature of thermal diffusion

∇T / group	10℃	8℃	5℃
1	25	23	20
2	22.7	21.4	19.3
3	20.3	19.2	18.2
4	18.7	18.7	17.5
5	17.9	17.9	16.8
6	16.4	16.9	15.9
7	15.1	15.3	15.1

∇T : Different temperature between pump water and recharge water

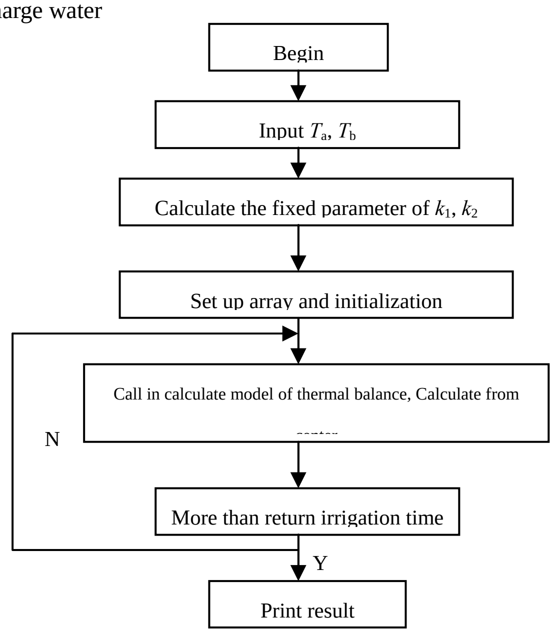

Fig.1 The flow chart of thermal balance calculation

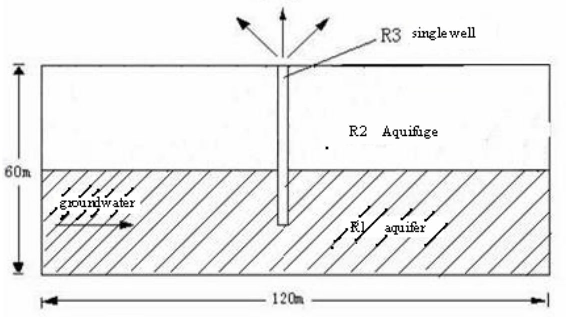

Fig.2 Physical model of single well temperature field

2) The mathematics model

In the MATLAB calculation, the convection and conduction problem belongs to the parabolic type partial differential equation. The calculation model is:

$$\rho C\frac{\partial T}{\partial t}-\nabla\cdot(k\nabla T)=Q+h\cdot(T_{ext}-T)$$

(2-4)

Where T is the temperature, ρ is the density, C is the specific heat, k is the conductivity coefficient, Q is the thermal source, h is the convective coefficient, T_{ext} is the environment temperature, $h\cdot(T_{ext}-T)$ is the thermal rate transmit from environment to region.

The mathematics model of this simulation is:

$$\frac{\partial t}{\partial\tau}=a\left(\frac{\partial^2 t}{\partial r^2}+\frac{1}{r}\frac{\partial t}{\partial r}+\frac{\partial^2 t}{\partial z^2}\right)$$

$$(r,z)\in\Omega\geq 0 \quad (2\text{-}5)$$

$$t(r,z,0)\big|_{\Gamma}=t_{\infty}(r,z),\quad (r,z)\in\Gamma \quad (2\text{-}6)$$

$$\lambda\frac{dt(r,z,\tau)}{dz}\Big|_{\Omega'}=0,(r,z)\in\Omega',\ \ \tau\geq 0$$

(2-7)

$$t(r,z,0)\big|_{\Omega}=t(r,z),\quad (r,z)\in\Omega \quad (2\text{-}8)$$

Where $t_{\infty}(r,z)$ is the infinitude far temperature in radius direction, Ω' is the heat storage well wall boundary, Ω is the 2D calculate region, $\Omega=\Omega_1+\Omega_2$, here, Ω_1 is heat storage layer, Ω_2 is not heat storage layer (namely up and down aquifer), Γ is the out boundary of calculate region (do not include heat storage well boundary), $t(r,z)$ is the initial temperature, including the series temperature attained from above calculation by thermal balance method, $a=\lambda/\rho c$ is the thermal diffusion rate of porous medium, here, λ is thermal dispersion rate.

2.3 The Temperature Field Simulation Analysis

By means of simulation, it can attain the least influence radius when the ∇T are 10 , 8 ,5 . It shows in Fig.3, Fig.4, Fig.5. Considering the need of well-group alternation, the distance between two well must be above two times of the least influence radius, so it can avoid temperature field overlay.

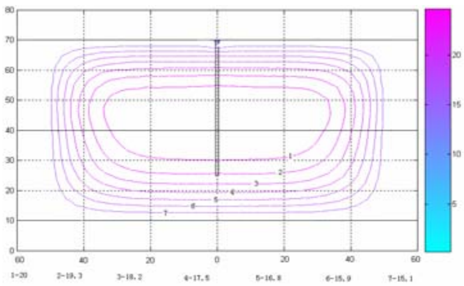

Fig.3 The single well temperature field for 5 temperature difference

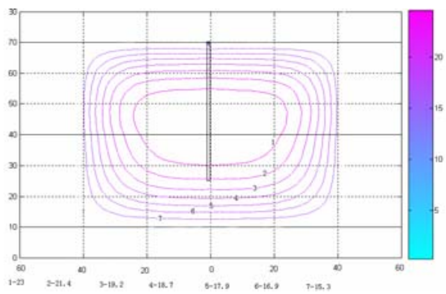

Fig.4 The single well temperature field for 8 temperature difference

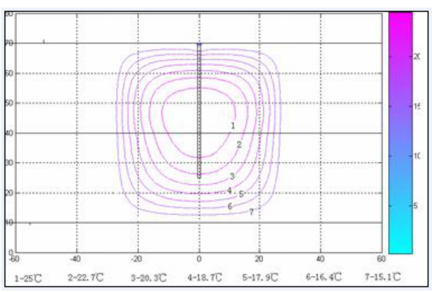

Fig.5 The single well temperature field for 10 temperature difference

After contrast, it can attain the conclusion: the flow rate and ∇T are the main factors that affect the thermal transfixion. When the pump load increasing, if enhancing water flow rate, the draw out water temperature will reduce, but the thermal influence region will increase and will reduce draw out water temperature reduction. If increasing ∇T, the getting heat region of aquifer and top, bottom rocky soil basically keeps invariable, but the thermal influence region will reduce and the draw out water temperature will drastically reduce. According to the three group data, introducing method of least squares, it fits out the curve between ∇T and the single well least influence radius(d). Finally, it gets the quadratic equation:

$$d = 58.6157 - 0.3193 \nabla T^{2} \qquad (2\text{-}9)$$

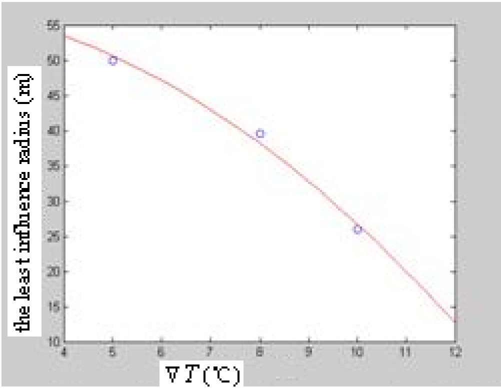

Fig.6 Quadratic fitting Curve between the least influence radius and ∇T

3 THERMAL TRANSFIXION ANALYZED AND WELL GROUP OPTIMIZED

3.1 Physical Model

As Fig. 7 and Fig. 8 shows, we have to discuss many kinds of distance of inter-well and both the length and width are indefinite, so the physical model regards that the length of the room as x axle and its value is X(m) , the direction of the width is y axle and its value is Y(m), the height direction is z axle and its value is 90m. Both the aquifuge and aquifer are 30m height. In order to ensure the recharge effect and assure the surface would not subside, it adopts non-impact recharge. The research area mainly medium is coarse sand, so the model setting two pump wells and a recharge well ,and the inter-well distance are Am, radius of wells are 400mm. The model interior is porous media. It makes several suppose: (1) steady state, laminar, incompressible, three-dimensional; (2) homogeneous and isotropic media; (3) natural convection fulfils the Darcy law; (4) water and saturation aquifer is thermodynamics balance.

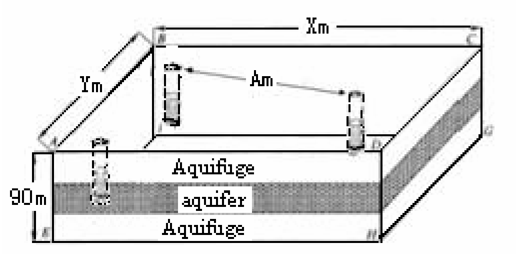

Fig.7 The simulation object physical model

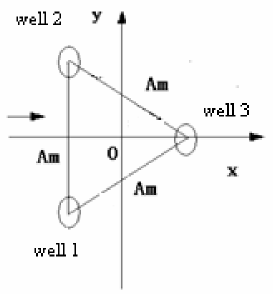

Fig.8 The simulation object section (z=0)

3.2 Mathematics Model

(1) Continuous equation:

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (3\text{-}1)$$

(2) Momentum equation:

$$S_i = \sum_{j=1}^{3} D_{ij} \mu \nu_j + \sum_{j=1}^{3} C_{ij} \frac{1}{2} \rho \left|\nu_j\right| \nu_j \qquad (3\text{-}2)$$

(3) Energy equation in Porous media:

$$\frac{\partial}{\partial t}\left(\phi \rho_f h_f (1-\phi) \rho_s h_s\right) + \frac{\partial}{\partial x_i}\left(\rho_f u_i h_f\right)$$
$$= \frac{\partial}{\partial x_i}\left(k_{eff} \frac{\partial T}{\partial x_i}\right) - \phi \frac{\partial}{\partial x_i} \sum_{j'} h_{j'} J_{j'} + \phi \frac{Dp}{Dt} +$$
$$\phi \tau_{ik} \frac{\partial u_i}{\partial x_k} + \phi S_f^h + (1-\phi) S_s^h$$

(3-3)

3.3 The Establish of Boundary Condition

1) Wall boundary

Including wall of a well and other default boundary, namely: V_x=0, V_y=0, V_z=0, K=0, ε=0, $\frac{\partial C}{\partial n}=0$,

Where n is the out normal direction of wall.

2) Velocity inlet (outlet) boundary

(1) Recharge well outlet boundary

The velocities on recharge outlet are equality and the streamline distributions are symmetrical in all directions:

V_x=0, V_y=0, V_z=-V_g

Where V_g is the recharge velocity

(2) Pump well inlet boundary

The velocities on pump well inlet are equality and the streamline distributions are symmetrical in all directions:

Vx=0, Vy=0, Vz$=2V_g$, $C=0$

(3) Aquifer inlet boundary

Including IJMN in the Fig.9, it takes the maximal average velocity of groundwater as 0.001m/s :

V_x=0.001, V_y=0, $V_z=0$, $C=0$

3) Outflow boundary

EFLK and QPGH are aquifuge outflow boundary, LKQP is aquifer outflow boundary.

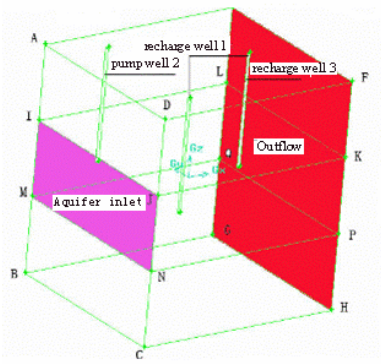

Fig.9 Reference model of boundary condition

3.4 Numerical Simulation Analysis of Inter-well Flow Field

1) The comparative analysis of flow field when fix up the velocity and change the inter-well distance

(1) The 5 temperature difference

As described in Fig.10，the curve denotes the streamline and the arrowhead denotes the velocity direction, a part of streamlines directly enter into pump well 2 from recharge well 1 and the thermal transfixion have happened, but it can't make sure the extent. It brings forward streamline analysis method and ascertains the inter-well thermal transfixion based on the trace and streamline superpose in steady state and incompressible zone. Provide the aquifer interior is the homogeneous and isotropic porous media, so the flux distribution is equivalent in all directions. It picks up 32 points around the mouth of the well and observes the flow condition of the streamline which passing those points, makes use of the streamline which directly enter into the pump well account for the value of the whole flux. So observing the Fig.10, 5 lines enter into the pump well and the others enter the outflow face, it gets the result that the thermal transfixion flux account for 5/32 of the whole flux. Observing the recharge well 3 and pump well 2, it has no thermal transfixion between them .

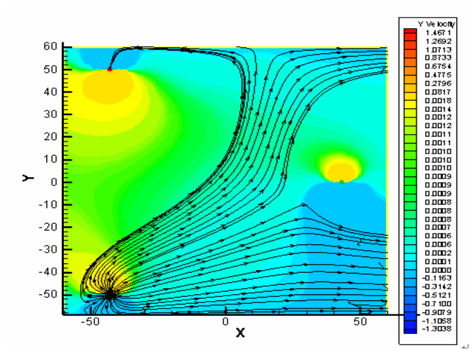

Fig.10 The streamline for V_g=2m/s and D_j=100m(Where: D_j: Distance among the wells group)

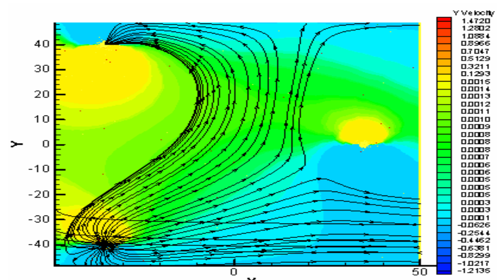

Fig.11 The streamline for V_g=2m/s and D_j=80m

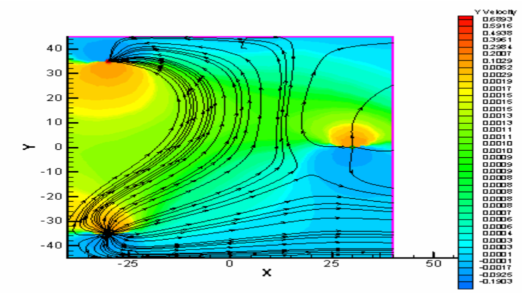

Fig.12 The streamline for V_g=2m/s and D_j＝70m

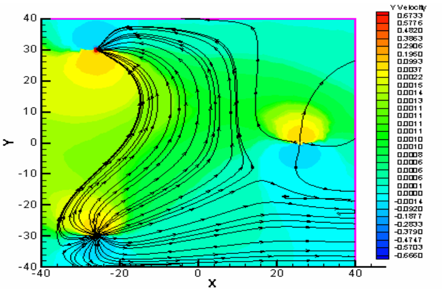

Fig.13 The streamline for V_g=2m/s and D_j＝60m

The extent of thermal transfixion decides the system performance. Reducing the inter-well distance can curtail investment greatly. We must analyze the flow field on different distance. The inter-well distance is 80m, 70m and 60m and their flow fields are shown in Fig.11, Fig12 and Fig13. From these figures we can get that the thermal transfixion have happened between the recharge well 1 and the pump well 2 in different extent, the value of the thermal transfixion is 13/32 when the inter-well distance is 80m, the value is 16/32 when the distance is 70m, the value is 18/32 when the distance is 60m. Noticing a great change, the thermal transfixion have happened among the three wells when the distance is 60m.

(2) The 8　temperature difference

As described in Fig.4, the single well least influence radius is nearly 40m and it has no thermal transfixion when the distance between the inter-well is over 80m. The Fig.14 indicates that: it has no thermal transfixion among the three wells and proves that the temperature distribution is right. In the Fig.15 and Fig.16, we can get that: observing the recharge well 1 and pump well 2, the value of the thermal transfixion is 4/32 when the inter-well distance is 70m; the value is 9/32 when the distance is 60m and it has no thermal transfixion between recharge well 3 and pump well 2.

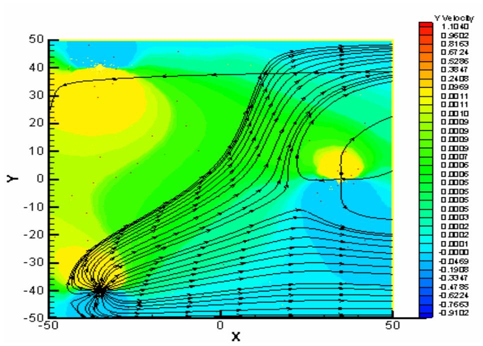

Fig.14 The streamline for V_g=1.4m/s and D_j＝80

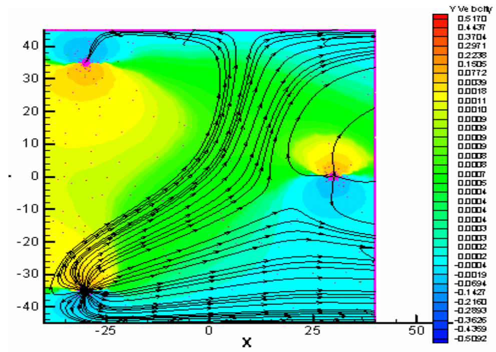

Fig.15 The streamline for V_g=1.4m/s and D_j＝70m

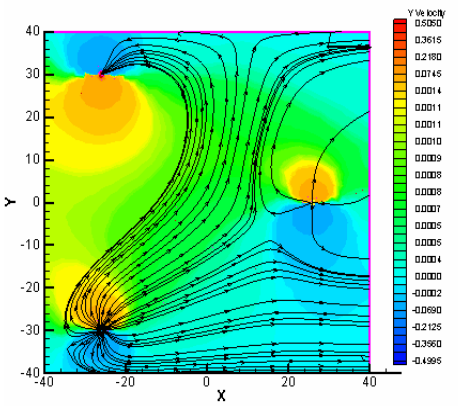

Fig.16 The streamline for V_g=1.4m/s and D_j＝60m

(3) The 10　temperature difference

There are no thermal transfixion among the three wells because the distance is two times longer than the single well least influence radius. The Fig.18 indicates that the thermal transfixion flow is 7/32 between recharge well 1 and pump well 2 and it has no thermal transfixion between recharge well 3 and pump well 2.

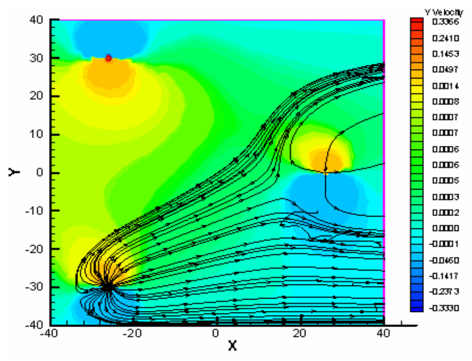

Fig.17 The streamline for V_g=1m/s and D_j=60m

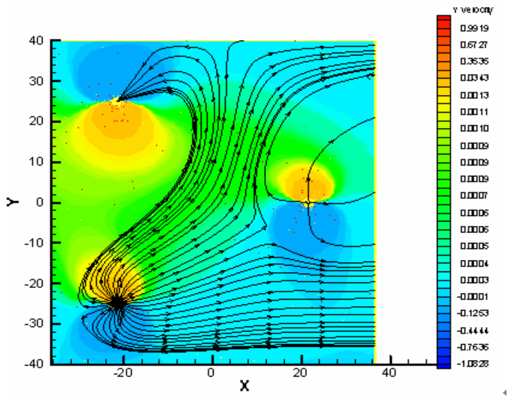

Fig.18 The streamline for V_g=1m/s and D_j=50m

2) The comparative analysis of flow field when fix up the inter-well distance and change the velocity

The flow field have some difference under the two operation situation of "small flux, large temperature difference" and "large flux, small temperature difference", the paper comparative analysis among 5 , 8 and 10 .

Tab. 3 Thermal transfixion analysis table

D_j \ ∇T	10	8	5
100m	none	none	5/32
80m	none	none	13/32
70m	none	4/32	16/32
60m	none	9/32	18/32
50m	7/32	13/32	20/32

As the Tab. 3 shows, we can find the extent of thermal transfixion on different inter-well distance and different temperature through the streamline analysis method. It gets the result that the thermal transfixion incessant increase along with the difference in temperature incessant reduce when fix up the inter-well.

4 CONCLUSION

(1) For the temperature field analysis, based on the least influence radius that calculated by the MATLAB, it can ascertain the least distance that avoids thermal transfixion under certain temperature difference. The data validity has been proved in the flow field analysis.

(2) Based on several hypotheses, for the extent of thermal transfixion, it puts forward "streamline analysis method" for the first time. The method can measure thermal transfixion rate in a certain extent.

(3) It is found that when the load keeps invariable, the well distance has a crucial influence on thermal transfixion. By the streamline analysis method, it analyses thermal transfixion rate under each condition. It shows in Tab.3 that: along with inter-well distance reducing, the influence that every same reduction of inter-well distance brings on thermal transfixion is reducing. But inter-well distance should better larger than the distance in which the two pump wells thermal transfix with recharge well.

(4) By the simulation, it is found that when the load keeps invariable, along with the ∇T increasing, pump water flux reduce and the thermal influence region shrink.

(5) For the influence of ground unit operation model, it should choose the model by practical project. After contrast, in the business zone, it should choose "small flux, large temperature difference" system, choose appropriate ∇T , to reduce well distance. The system can avoid thermal transfixion and save soil resource, but there is a problem of unit matching. While in the soil resourceful area, it can choose the familiar model: "large flux, small temperature difference". It is easy to choose equipment.

REFERENCES

[1] Y.-Y.Yan, T.-F.Lin. Evaporation Heat Transfer and Pressure Drop of Refrigerant R-134a in a Plate Heat Exchanger, Transaction of the ASME Journal of

Heat Transfer,1999,Vol.121,Feb:118-127；

[2] Zhang Zhihui etc. Nature convection impact on groundwater thermal transport research. Hydrology geology and engineering geology，1995，（4）：16-18；

[3] Wang Jingguo, Zhou Zhifang etc. Coupled method of BEM-FAM for simulation of ground water thermal transport. Shui Li Xue Bao ,2001,5:71-76

[4]Bear J. Dynamics of fluids in porous media. American Elsevier Publishing Company Inc,1972.

[5] Prickett, Naymick, Lonnquist, 1981. A “randomwalk” solute transport model for selected groundwater quality evaluations. Illinois State Water Survey, Bulletin, vol. 65: 103-107

[6] S. Chevalier, O. Banton. Modelling of heat transfer with the random walk method.Part 1. Application to thermal energy storage in porous aquifers, Journal of Hydrology 222 (1999): 129–139

[7] Sudicky，Mclaren. The Laplace Transform Galerkin technique large-scale simulation of mass transport in discretely fractured porous formations. Water Resources Research. 1992,(2):36-41

[8] XUE Yuqun, XIE Chunhong. LI Qingfen.Aquifer thermal energy storage:a numerical simulation of field experiments in china. Water Resources Research. 1990,(10):16-21