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The Coupling Model of Flow and Heat Transfer of Aquifer Thermal Energy Storing and its Numerical Analysis

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Abstract: Aquifer's thermal energy storage process is directly related to the water distribution around the single well while water is drawn out or recharged into the aquifer, especially related to the water distribution when it recharged into the aquifer half a year later. Coupling groundwater's fluid model with heat transfer model should compose heat transfer mathematical model of groundwater. When considering the energy storage capacity of aquifer and choosing position of the well accurately, it is as far as possible to consider the original groundwater's flow. As long as the law of the flow in the aquifer matches the Darcy's law, whether recharging or pumping the energy-storing groundwater, this coupling model is always applicable. Computing result has enough precision, which is the credible basis for designing the aquifer's thermal energy storage engineering.

Key words: aquifer; flow; heat transfer; coupling model
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1. Introduction

For saving conventional energy resources and reducing large amount of waste gas discharged from fossil fuel's burning, more and more countries and organizations propose the strategy of sustainable energy and recommend utilizing renewable, pollution-free resources in a more cost-effective manner. The geothermal energy is just one of the energy which accords with this condition.

In order to draw underground thermal energy, underground energy storage technology (Underground Thermal Energy Storage, UTES) is a satisfying scheme. This technology includes two categories: the closed-loop heat exchange system and the open-loop heat exchange system. In the former, the circulating water driven by a heat pump absorbs heat or cold from aquifer through an underground pipe. In the latter, however, the groundwater will be drawn to provide heat or cold for users directly. What's more, in the former system the circulating water exchanges heat with the geothermal environment by heat conduction through well's wall, while the latter system uses water from underground directly. There is not only a course of heat conduction, but also a mass transfer in the latter system. Therefore, the former's efficiency of utilizing geothermal power is inferior to the latter.

The open-loop heat exchange system operate in two modes: (1) Collecting the groundwater and utilizing its thermal energy through a heat pump, afterwards discharging it into the sewer or surface water. The shortcoming of this system is obvious. (2) The thermal energy having been absorbed, groundwater is charged into the underground again. In this mode, the groundwater is used but not consumed and its thermal energy is utilized cyclically.

Making thorough exploration on aquifer's thermal energy storage technology (ATES) began in 1960s of the last century. At that time, Shanghai municipality artificially replenished the groundwater in order to control the surface subsidence because of the excessive pumping groundwater for industrial use. Two kinds of aquifer thermal energy storage technologies were invented, namely, winter's charging for summer's cooling and summer's charging for winter's heating. The development of these two technologies began in the early 1980s of last century, and the first program of aquifer's thermal energy-storage was realized in the late 1980s of last century in abroad.

The research on heat transfer and flow in aquifer has been performed, however, there are just a few documents dealing with concrete analysis of flow and heat accumulation in aquifer during the energy storing processes. The characteristics of heat transfer and flow in underground aquifer are basically similar to that of ordinary groundwater, and each has their own characteristics. The coupling formula for heat exchange combined with water flow is a practical model.

In physics, "coupling" means a kind of mutual affecting and interactive phenomena from two systems or two motion modes, which influence each other so as to join up together at last. Usually, analyzing coupling process's feature depends on the properties of the said coupling. The analyzing process may have the aid of two different methods, of which one is a sequence coupling and the other, is a direct coupling. Here the sequence coupling method is utilized, that is, the result of the first analysis becomes the condition of the second one. For an interactive situation without severe nonlinearity, utilizing sequence method to solve problem is a suitable procedure.

Aquifer's thermal energy storing process is composed of thermal convection system, thermal conduction system and groundwater flow system. They interact on each other. The definite solutions of flow and heat transfer link with each other by the velocity of flow to form a coupling model of aquifer's thermal energy storing. The confined aquifer is often selected for thermal energy storing, in which the flow is regarded as horizontal laminar flow and temperature's influence on the characteristic of flow, porosity and permeability, can be neglected.

2. Flow's characteristics of underground aquifer's energy storing

The confined aquifer is generally chosen as the aquifer for storing thermal energy. In this kind of geologic framework structure, main deformation occurs in the vertical direction (Δz), and almost no deformation in X and Y direction. The porosity of aquifer is a variable, while density of water is constant. So, the continuity equation is:

$$\left[\frac{\partial}{\partial x}\left(K_x\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial H}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial H}{\partial z}\right)\right]\rho\cdot\Delta z=\frac{\partial}{\partial\tau}(\rho\varphi\Delta z) \qquad (1)$$

After transformation:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial H}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial H}{\partial z}\right)=\mu_s\frac{\partial H}{\partial\tau} \qquad (2)$$

Here, $\mu_s=\rho g(\alpha+\varphi\beta)$, water's dilution rate; α, compressibility coefficient of aquifer's granule framework; β, water's elastic compressibility coefficient; φ, porosity; H, water head; K_x, K_y, main permeability coefficient along X and Y; M, thickness of aquifer.

Suppose: the confined aquifer's thickness is constant in horizontal direction; the permeation flow is a horizontal two-dimensional flow. Order:

$$K_x\cdot M=T_x$$

$$K_y\cdot M=T_y$$

and $\mu*=\mu_s\cdot M$

The above formula can be simplified as:

$$\frac{\partial}{\partial x}\left(T_x\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y\frac{\partial H}{\partial y}\right)=\mu*\frac{\partial H}{\partial\tau} \qquad （3）$$

For isotropic and homogeneous confined aquifer, two-dimensional equation for unsteady flow can be further simplified as:

$$\frac{\partial^2 H}{\partial x^2}+\frac{\partial^2 H}{\partial y^2}=\frac{\mu^*}{T}\frac{\partial H}{\partial\tau}$$

（4）

The thermal energy storing process in underground aquifer has a direct correlation with the state of charging and pumping of a single well, especially, with the state of charging process half a year later. Formula (2), (3) or (4) are for general use, however, the water flow process in aquifer for energy-storing also satisfies them.

3. The model of heat transfer in underground aquifer's energy-storing

Heat transfer in groundwater is a complicated process, including transmittance of water-flow and transference of heat-flow concurrently. The heat transference concerns groundwater and is related with the medium the groundwater adjoins. It also has a close relation with groundwater's motion status. That is, the heat transference is a coupling of two kinds of physical fields in a same medium [11].

The heat exchange course between water and aquifer is supposed to finish instantaneously. After water at certain temperature is infused into aquifer, there will be a temperature gradient between the water and rock stratum. And then, heat exchange takes place inevitably. The time lasting for the course of reaching balance is called heat exchange balancing time. Its length depends on some factors, such as aquifer's state, water flow's behavior. Houpeurt et al [14] measured the heat exchange balancing time under the condition of medium with different grain size in the laboratory. However, there are no examples which take the water-rock heat exchange into consideration in the numerical simulation of aquifer's heat transfer. Now the medium of aquifer and groundwater are considered as a whole; the heat exchange between water and rock is supposed to finish instantaneously so that they have the same temperature all the time.

Generally, the aquifer suitable for energy storing is often rather gently. Furthermore, the influence of charging water is at a small area compared with this whole aquifer. Certainly, thickness of the calculating domain can be reasonably considered as a constant. Thus, the flow is of two-dimension; there is no flow in Z direction.

Take the Infinitesimal illustrated in Fig. 1 as an analytic target, according to the first law of thermodynamics:

Heat Q_1 entering into the infinitesimal with conduction + heat Q_2 entering into the infinitesimal with water flow = the enthalpy growth ΔH of water and framework structure in the infinitesimal

In order to discuss the situation with stable physical properties, the heat quantity entering the infinitesimal with conduction should be analyzed. Let c_w represent specific heat at constant pressure, from Fourier law, the temperature of water and framework structure in the infinitesimal changes by $\frac{\partial t}{\partial \tau} d\tau$ in a time interval $d\tau$. Its enthalpy growth is:

$$\begin{aligned}\Delta H &= \Delta H_1 + \Delta H_2 = c_w \rho \varphi dxdydz \frac{\partial t}{\partial \tau} d\tau + c_s \rho_s (1-\varphi) xdydz \frac{\partial t}{\partial \tau} d\tau \\ &= [c_w \rho \varphi + c_s \rho_s (1-\varphi)] dxdydz \frac{\partial t}{\partial \tau} d\tau\end{aligned} \qquad (5)$$

So, the differential equation of energy transference in a confined aquifer with a constant horizontal thickness is:

$$\begin{aligned}&\left(\lambda_x \frac{\partial^2 t}{\partial x^2} + \lambda_y \frac{\partial^2 t}{\partial y^2} + \lambda_z \frac{\partial^2 t}{\partial z^2}\right) dxdydzd\tau - \rho_w c_w \left(v_x \frac{\partial t}{\partial x} + v_y \frac{\partial t}{\partial y}\right) dxdydzd = \\ &[c_w \rho_w \varphi + c_s \rho_s (1-\varphi)] dxdydz \frac{\partial t}{\partial \tau} d\tau\end{aligned} \tag{6}$$

or：

$$\lambda_x \frac{\partial^2 t}{\partial x^2} + \lambda_y \frac{\partial^2 t}{\partial y^2} + \lambda_z \frac{\partial^2 t}{\partial z^2} - \rho_w c_w \left(v_x \frac{\partial t}{\partial x} + v_y \frac{\partial t}{\partial y}\right) = [c_w \rho_w \varphi + c_s \rho_s (1-\varphi)] \frac{\partial t}{\partial \tau} \tag{7}$$

Because the heat conduction process takes place in porous medium which consists of two kinds of materials, its parameters have particularity. Here, λ is comprehensive coefficient of thermal conductivity of the infinitesimal; ρ_w is density of water; ρ_s is density of framework structure; c_w is specific heat at constant pressure; c_s is specific heat of the framework structure; φ is porosity; v_x, v_y are permeation velocity in X and Y direction, representing the virtual velocity of water while the flowing is full of the cross section.

4. The coupling model of heat transfer and flow in aquifer's energy-storing

The mathematical model of heat transfer in underground aquifer is made up of groundwater flow model, heat transference model and a motion equation of groundwater flow, which is from the former two models' coupling. From the analysis above, for the two dimensional situation neglecting the natural convection from density's variation caused by temperature difference, the groundwater flow model can be:

$$\begin{aligned}&\frac{\partial}{\partial x}\left(T_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_y \frac{\partial H}{\partial y}\right) = \mu * \frac{\partial H}{\partial \tau} \\ &H(x,y)|_{(x^2+y^2=r^2)} = H_0(\tau) \qquad \text{(r: the radius of the recharge well)} \\ &-K \frac{\partial H}{\partial x}|_{x=x'} = v_0 \\ &-K \frac{\partial H}{\partial y}|_{y=y'} = 0\end{aligned} \tag{8}$$

Here, x' and y' mean places where the energy storing water was not reached.

The motion equation of the water-flow is：

$$v = -K_x \frac{\partial H}{\partial x} i - K_y \frac{\partial H}{\partial y} j$$

（9）

The heat transfer model of the aquifer’s energy-storing：

$$\lambda_x \frac{\partial^2 t}{\partial x^2} + \lambda_y \frac{\partial^2 t}{\partial y^2} + \lambda_z \frac{\partial^2 t}{\partial z^2} - \rho_w c_w \left(v_x \frac{\partial t}{\partial x} + v_y \frac{\partial t}{\partial y} \right) = \left[c_w \rho_w \varphi + c_s \rho_s (1-\varphi) \right] \frac{\partial t}{\partial \tau} \qquad (10)$$

$$t|_{\Gamma_0} = t_0$$

$$t|_{\Gamma_1} = t_1$$

$$t|_{\Gamma_2} = t_2$$

$$t|_{(\text{water filling})} = t_3(\tau)$$

Γ_0，Γ_2 and Γ_2 represent the initial temperature profile of the original aquifer, of the aquifer’s top surface and of the aquifer’s bottom surface, respectively.

5. The model’s correctness and accuracy

The differential formulation of the coupling model for flow is derived from the flow’s continuity equation combined with Darcy's law. So long as the water flow in underground aquifer satisfies Darcy's law, this differential formulation must be tenable. No matter artificial recharging or pumping work must be performed under the condition of water permeating flow. Otherwise, the underground aquifer’s framework structure around the energy storage well shall be destroyed permanently. Therefore, this formulation coincides with the practical application perfectly.

In the process of thermal energy storing, heat transfer takes place in underground aquifer. It includes heat conduction, flow and heat exchange from the temperature changing of the aquifer’s framework structure. In the differential equation of the aquifer’s heat transfer, their mathematical expressions are the term of heat conduction, the term of flow’s heat transfer and the term of enthalpy growth. With a deducing process based on Fourier Law together with energy conservation law, a differential equation of energy is arrived at. The equation includes a term of flowing and so, the coordination of conduction effects and convection effects in water flowing may be described.

Aquifer’s geological structure is complex with different permeation coefficients in various directions. This difference may be manifested in different value of permeation coefficient. Grids’ partitioning method is the guarantee of calculation’s accuracy. The grids’ arrangement must cover the intact aquifer structure; otherwise the results of the calculation will be distorted and not true to the original. So long as the data are enough, the calculation results can attain a satisfied accuracy by means of finite element method and grids’ subarea method.

From theoretical research, the convection influence should be considered in the analysis of energy transmission. But the convection is almost impossible to take place because the aquifer is influenced by the original groundwater’s horizontal flow for a long time; permeation coefficient in horizontal direction is much greater than that in vertical direction. Some research and experiment[10] also indicates that only under the condition of smaller permeation coefficient will obvious convection appear. While energy storing water is infused into well pipe, the water near the well flows fast. The farther it is away from well, the slower it flows. The convection occurs near the periphery of the water infused only. With little heat dissipation, the water temperature near the periphery is close to that of the framework structure. The course of infusion will usually last a period of two or three months. After that period, the temperature difference between the energy storing aquifer and the upper or lower aquifuge is very small, while temperature difference in the horizontal direction outside the well is large. It may be inferred that heat transfer can only occur in aquifer’s horizontal direction. That is, neglecting natural convection in calculation is reasonable.

In sum, both flow and heat transfer differential equations of the coupling model have precise physics meanings. Having analyzed the characteristics of the groundwater flow and heat transfer under the energy storage condition, the instantaneous coupling model qualified to practical application may be established. Supported by computers, this model can obtain dynamic numerical simulation results with enough accuracy.

6. Prediction of aquifer’s energy storing process in Shanghai

This simulation model was once used for the prediction of underground aquifer’s energy storing process in Shanghai. The result of calculation proved this model’s accuracy and practicality.

The simulation must research the geological condition of underground aquifer in Shanghai, and so the hydro-geological parameters in Shanghai should be selected for calculation (Table 1). The aquifer is supposed homogeneous and isotropic. The calculation domain is an area of 240m×160m rectangle, in which two energy storing wells, with diameter of 4m, are arranged (Fig. 3).

The result of calculation is shown in Figures 2, 3 and 4. These figures offered the distribution of hydraulic isobaric line, hydraulic funnel and isothermal line after a succession of charging and pumping for 80 hours.

Fig. 2 shows the shape of hydraulic “funnel” formed after a succession of charging and pumping. It is manifested that the range of the water flows is wider in the horizontal direction than that in the vertical direction. This result suggests that the locations of different series of wells built for energy storing should keep enough horizontal interval, otherwise unnecessary mutual interference will be inevitable.

Corresponding to a succession of charging and pumping, the hydraulic isobaric line and groundwater’s flow status are displayed in Fig 3. The arrows represent the direction of flow velocity vector. This figure has shown the remarkable function produced by the horizontal mobility of the original groundwater in aquifer. Because of this function, the flow of charging water against the pumping direction is much weaker than that in the pumping direction along X-axis. Along Y-axis, the groundwater flow just produces the transverse excursion effect; this influence caused is comparatively weak. However, the aberrantion produced by the distortion of the whole flow field is obvious.

Fig 4 is the relevant distribution of temperature. This figure clearly shows the eccentric transference of the temperature field and manifests the influence of original groundwater flow.

The calculation result listed above is similar to the posture of the figures provided by the same category's problems of research in home and abroad. This indicates that the calculation of this model can reflect the real process of flow and heat transfer in underground aquifer. The result of simulation has especially clearly shown the impact on the aquifer's energy storing caused by steady flow.

7. Conclusions

Proceeding from analyzing the characteristics of aquifer's flow in thermal energy storing, the coupling model of flowing process and heat transfer process together with simulation on their integrated variations shall be able to improve the numerical analysis's accuracy, compared with a discrete model considering the flow and heat transfer separately.

While analyzing aquifer's thermal energy storing ability and choosing the well's location, the flow behavior of original groundwater should be taken into consideration as full as possible.

Because the coupling model can calculate the heat quantity from heat-conduction and groundwater flow, even no consideration put on the time effect of heat exchange between water and rocks and influence of natural convection, the simulation can still attain enough accuracy in a large area around the well.

Having considered the characteristics of charging flow from a single well and calculated the effects of sustained flow of the original groundwater, a long period's flow situation and temperature distribution may be described precisely.

So long as the groundwater flow in aquifer accords with the condition of Darcy's law，this coupling model will be suitable for both the processes of recharging and pumping in groundwater.

Supported by abundant observation data, this coupling model can carry out the dynamic simulation on groundwater's thermal energy storing. On this basis, the interaction of the wells in a twin-well system or a multi-well system can be analyzed; and the thermal influence's range of the wells used for several years can be determined.

This coupling model can manifest the comprehensive effects of flow and heat conduction. Its calculation can reflect the water funnel's posture and influence faithfully. The model can also calculate groundwater's transmission and heat exchange under various kinds of border terms and initial values. The result of calculation has enough precision to offer the reliable basis for the engineering design of aquifer's thermal energy storing.

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Table 1 Calculation parameter

permeability coefficient, K （m/d）	30	specific heat capacity of framework structure， c_s （$kJ/kg\cdot k$ ）	0.92
Water dilution ratio, μ_s （m^{-1}）	7.45 × 10^{-5}	Density of water, ρ_w （kg/m^3 ）	1000
Porosity, φ	30%	density of framework structure ρ_s （kg/m^3 ）	1840
thickness of aquifer, M (m)	40	Overall heat transfer coefficient of infinitesimal， λ （$W/m\cdot k$ ）	0.437
Water head, H (m)	28.93 ～ 27	Radius of well， r （m）	2
specific heat of water， c_w （$kJ/kg\cdot k$ ）	4.172	original velocity of groundwater flow， v_0 （m/d）	0.2
amount of water recharging(pumping) per hour （m^3）	100.54	total amount of water recharging(pumping) （m^3）	8043.2
original temperature of groundwater， T （℃）	20	Temperature of recharging water，T （℃）	32

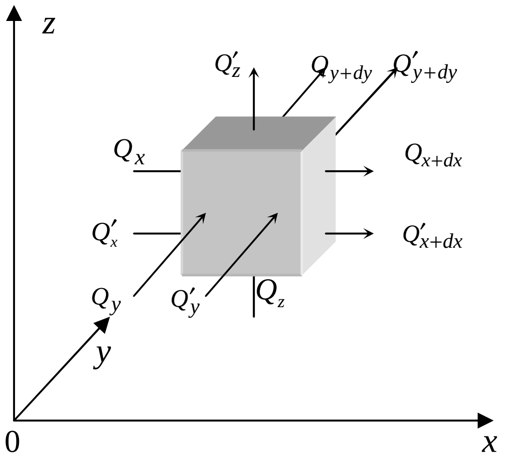

Figure 1 Heat in and out the infinitesimal

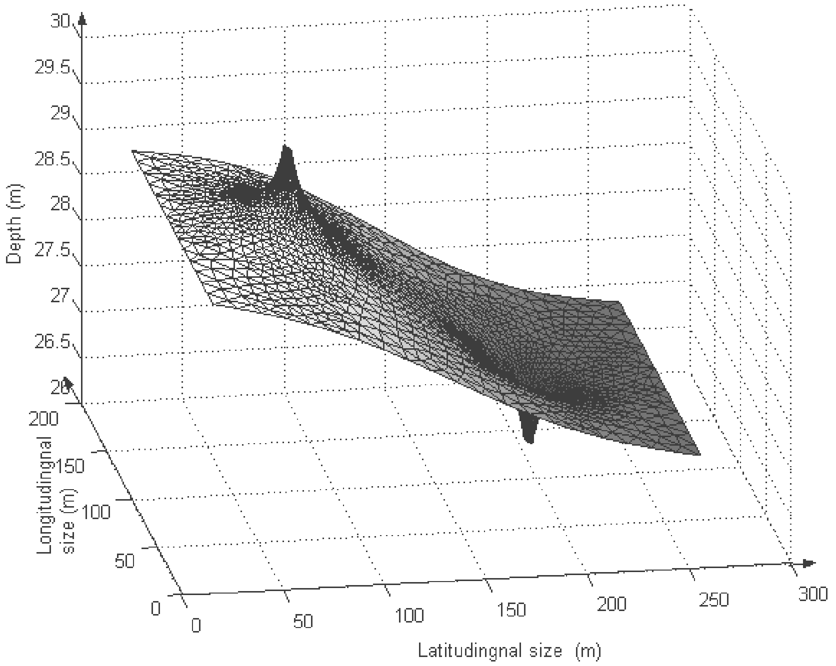

Figure 2 Recharging funnel and pumping funnel

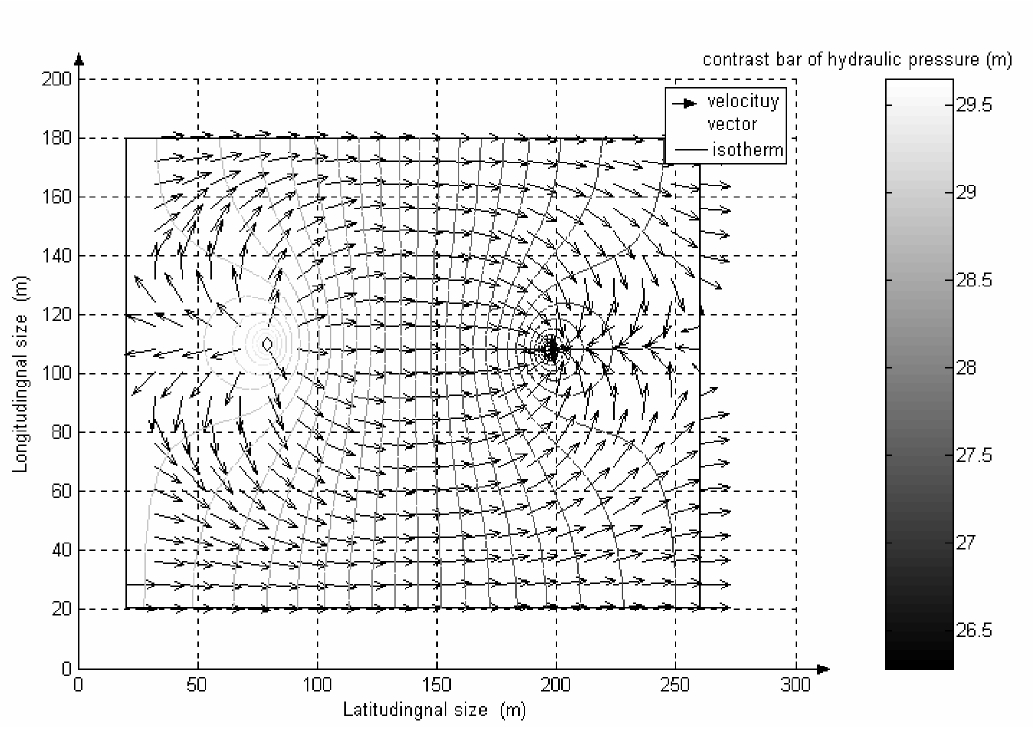

Figure 3 The isobaric line and the flow of groundwater

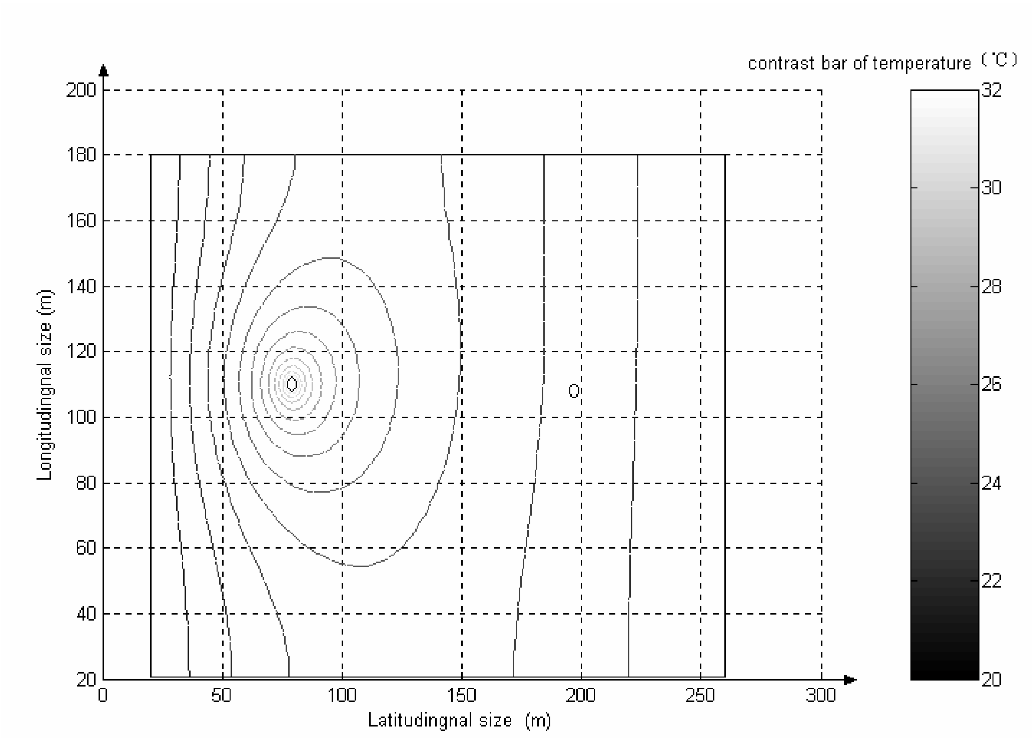

Figure 4　　**Distribution of isothermal line**

Symbols

μ_s：　Water dilution ratio　m^{-1}；

α：　compressibility factor of aquifer grain framework

β：　elastic compressibility factor of water

φ：　porosity；

M：　thickness of aquifer　m；

v_x, v_y：　permeation velocity　m/day；

H：　water head(L)、enthalpy growth（kJ/kg）；

K_x、K_y　major permeability coefficient in X or Y direction　m/day；

r：　well radius　m；

Q：　heat amount into the infinitesimal by thermal conduction　W；

λ：overall heat transfer coefficient of infinitesimal　$W/m \cdot k$；

T： temperature k ；℃

τ： time；

c_w, c_s : specific heat of water, of framework structure $kJ/kg \cdot k$

ρ_w, ρ_s： density of water and framework structure kg/m^3