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Choosing and Arranging of The Aquifer Thermal Energy Storing Well's Position

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Abstract: By means of the aquifer's thermal energy storing technology, winter's cool from the nature can be stored for building's air conditioning in summer and on the contrary, summer's heat from the nature stored, for building's heating in winter. A comprehensive analyzing of aquifer's geologic characterizes ascertains that the confined aquifer is the suitable aquifer for thermal energy storing, and that the storage mode is supposed to adopt the mode of thermal energy storage in same layer. Influence radius of single well can be predicted through analyzing the thermal equilibrium and the thermal diffusion. Reasonable arrangement of the thermal wells can avoid the influence of original groundwater flow and of the variance of permeability coefficient. Utilizing the coupling effects of infiltration between thermal energy storage wells, arranging special well between thermal energy storage wells and controlling the range of thermal energy water initiatively, can obtain the compact result for arrangement between thermal energy storage wells.

Key words: aquifer thermal energy storage, same layer project, influence radius

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1. Introduction

The groundwater temperature varies with natural geographical surrounding, geological condition and the depth at which the water cycle is. Under epilimnion, which is near the ground surface, a constant temperature zone is at a certain depth, where the water temperature is little affected by solar radiation. Early in 1960's Sun Yongfu, a Chinese Scholar, put forward a scheme of Aquifer Thermal Energy Storage (ATES) to supply cold resources for air-conditioning at Shanghai's textile mills in summer, and meanwhile to resolve surface subsidence from excessive charging of underground water. Since 1976 research in this field aroused wide interests of scientists around the world so that many research organizations reported their project results of site experiments and mathematical simulations, such as University of Nechatel in Switzerland, University of Auburn in America, the Geology Survey Bureau of the United States and the Geology & Mining Research Office of France. Some demonstrations were carried out in Switzerland, Germany and France. A TEMPO report issued by American GE Company discussed the role of ATES technology in future American energy system. The same year, NATO's Science Committee held a conference in Turnberry, Scotland to encourage developing the ATES concepts. ATES system is of great energy capability with a low construction cost and non-emission operation, suitable for large scale of air-conditioning systems in exhibition halls, gymnasiums, building complexes, large markets and waiting rooms. As an energy saving technology for cold supply and heat supply with economy, reliability and stability, ATES utilizes water storing structures in underground rock strata, such as gaps, cracks, karst caves. Because underground water flows in aquifer at a very low velocity with a little temperature variation, it is convenient to store both of the seasonal energy, abundant cold in winter and cheap heat in summer, into the aquifer by means of charging water through tube wells for air-conditioning's needs.

Although ATES conforms the trend of sustainable development [1][2], there are a series of problems in its application, such as, the surface subsidence, the pollution of aquifer, the systems' commercial gains and so on. The first step for resolving the above problems is to arrange the storage wells reasonably, to avoid the heat transmission between the wells. As a result of thermal diffusion and aquatic infiltration, the influence radius of the storage wells becomes larger and larger with the time extending. The heat transmission cannot be avoided merely by increasing the distances between wells. The feasible approach is an arranging scheme of special wells, which is worked out from filling water's thermal diffusion, from the coupling effects of underground water's natural permeation and from infiltration between the wells.

So far as energy saving, phreatic aquifer is superior to confined aquifer. Phreatic aquifer's location near the earth's surface results in less investment in energy storing wells, easier for refilling, larger capacity of water storage, more approaches for water supplying and so on. However, its disadvantages are obvious. The upper neighbor is the earth's surface and so, the wastewater from industry and water polluted by living garbage may permeate into the phreatic aquifer. Then it is difficult for filling water to reach the quality required by energy storage equipments. Meanwhile, there are often buildings above phreatic aquifer, which will lead to large area of surface subsidence and tremendous economic loss once excess water is pumped out. Therefore, confined aquifer should be chosen as the aquifer for thermal energy storing.

2. Same layer and different layer of aquifer for storing thermal energy

Generally, a group of two wells can meet the needs of aquifer thermal energy storage. They work in a cyclical pattern of filling and pumping alternatively. Different-layer project is a good choice, namely, to arrange two wells in different layers of aquifer so that their mutual interference will be eliminated.

In application of different-layer project two wells, one storing warm water and another storing cold water, are dug to different layer of aquifer. Higher temperature of water is in a deeper layer, where the warm well may be arranged to play a big role for storing warm water. At the beginning of ATES technology application, a majority of wells adopted this arrangement.

The structure of the stratum indicates the age of the earth. Different layers came into being during different period; the composition of each layer is unique. Confined aquifer hides deeply in the earth; water in different layers has been there for a long time with different characteristics. Changing temperature of water in the same layer of aquifer leads to loose original balance and so, some unknown chemical reactions may take place there. Then, the aquifer's framework structure will be destroyed. In different-layer project, water of different characteristics will mix under veried temperature. In this way more chemical reactions may take place to destroy aquifer's framework structure permanently. On the other hand, this project has some effects on environment and engineering, e.g., storing wells' invalidation. As a result, the usage of different-layer project is shortened now and the energy-storing wells are often arranged in same layer of aquifer.

3. The influence radius of the energy-storing wells in same layer's aquifer

Arranging energy storing wells in same layer's aquifer means the determination of their separation intervals and relative positions. Firstly, the influence radius of a single well is predicted. Secondly, the features of original underground water flow may be analyzed. Thirdly, a comprehensive view of various factors can be taken and then, the regulating wells may be arranged reasonably to realize the man-made control at the thermal influence area.

The influence radius is a vertical distance between energy storing wells and the area, where the temperature of underground water is changed by 1% margin by charging energy storing water's permeation and thermal scattering. The direct way to predict the influence radius is the resolution by means of a mathematical model for underground water's heat transmission. The heat transmission is a complex process, related with underground water and the ingredients dissolved in water. This process is accompanied with the processes of flows and heat transmission in underground water as well as the ingredients dissolved in water. And so, it is a coupling of two physical fields in one medium.

Buscheck[5], Molson[6] and some others[7][8] have taken the influence of natural convection into consideration for aquifer thermal energy storage's simulation to improve their numerical solutions. Houpeurt et al[9] measured the time interval for keeping the equilibrium of heat transmission under experimental condition with different grain size of mediums. So far, however, there's no one model to cover all the influential factors. Actually, the duration for water charging and drawing is much shorter than half a year. It is reasonable to ascertain the thermal influence area roughly by the analysis of the heat transmission equilibrium and then, on the basis of which thermal diffusion can be determined and the analysis shall be simplified.

The analyze processes are as follows.

Fill a certain quantity of water (G, in ton), which occupies space in aquifer with a volume of radius,

$$R = \sqrt{G/(\pi h \eta)} \qquad （1）$$

where, h - the thickness of the aquifer；η - the porosity of the grit. If each filling of water at a certain quantity, the difference of last radius squared and initial radius squared is the same while water spreads outward. The former underground water in the space is repelled to the outer of the circle. And then, heat exchange will take place between water at temperature t_0 ℃ (the filling water's temperature) and grits at temperature t_a ℃ (the original underground water's temperature).

The equilibrium temperature t_{11} corresponding to the radius R_1 can be worked out:

$$G \times \rho_{\mathrm{w}} \times C\mathrm{w} \times (t_{11} - t_0) = \pi \times R^2 \times h \times (1-\eta) \times \rho_{\mathrm{g}} \times C_{\mathrm{g}} \times (\mathrm{t}_{\mathrm{a}} - t_{11}) \qquad (2)$$

Among which:

ρ_{w}: the density of water; C_{w}: the specific heat of water; t_{11}: the equilibrium temperature; ρ_{g}: the density of grit; C_{g}: specific heat of grit. While the second filling of water (G, in ton) at t_0 ℃, the first filling of water at t_0 ℃ is repelled to outer area beyond outer circle of radius R_2 . And so, we can get

$$R_2{}^2 - R_1{}^2 = cons\tan t$$

Now, heat transfer between the fresh filling of water at t_0 ℃ and the grit at t_a ℃ will take place. Then a new equilibrium temperature t_{21} corresponding to the radius R_1 can be worked out. Heat transfer between water at t_{11} ℃ and grit at t_a ℃ takes place, an equilibrium temperature t_{22} corresponding to the radius R_2 can be worked out. The rest may be deduced by analogy until all the filling water is charged. The drawing process is just the reverse.

Thus, a series of temperature corresponding to different radius may be solved. On the basis of the solution, the thermal diffusion analysis may be performed with the help of a mathematical model:

$$\begin{cases} \dfrac{\partial t}{\partial \tau} = a(\dfrac{\partial^2 t}{\partial r^2} + \dfrac{1}{r}\dfrac{\partial t}{\partial r} + \dfrac{\partial^2 t}{\partial z^2}) & (r,z) \in \Omega, \tau \ge 0 \\ t(r,z,0)|_{\Gamma} = t_{\infty}(r,z) & (r,z) \in \Gamma \\ \lambda \dfrac{dt(r,z,\tau)}{dx}|_{\Omega'} = 0 & (r,z) \in \Omega', \tau \ge 0 \\ t(r,z,0)|_{\Omega} = t(r,z) & (r,z) \in \Omega \end{cases} \qquad (3)$$

where, $t_{\infty}(r,z)$: the temperature at infinity in the radius direction; Ω': the boundary on the energy storing well's wall; Ω: a calculating area of two dimensions; $\Omega = \Omega_1 + \Omega_2$; Ω_1: the energy-storage layer, Ω_2: the upper or lower aquiclude layer; Γ: the outside boundary of the calculating areas, excluding the boundary of the energy-storing well; $t(r,z)$: the initial temperature, including the series of the temperature calculated from the thermal equilibrium; $a(=\lambda/\rho c)$: the thermal diffusivity of porous medium; λ: the thermokinetic dispersion coefficient.

The influence of natural convection is neglected throughout the calculating above, because it little affects the influence radius and mainly determined the stratification wjthin the cold water layer and hot water layer. Having got several parameters, the quantity of refilling water, the porocity and the thermokinetic dispersion coefficient etc., the influence radius of the the energy-storing wells may be predicted readily.

A simulating calculation has been done with the figures of such an experiment in Shanghai. The thickness of the aquifer is about 40 meter; the quantity of the refilling water is 92000 ton per year, the charging water, at 32□, is about 80% of the refilling water's quantity. The influence radius of the second year may be arrived at if original local water is at 21□.

From the isotherm in Fig.1 we can find the influence radius of the second year is no more than 50 meter and it would enlarge as the time goes on. We can figure out the influence radius in the coming years with this model.

4. Arranging the energy-storing wells in the same aquifer layer

There is no problem for arranging a single energy storing well if only one well is needed in a system. In this case the influence radius can be figured out by the method mentioned above. Now the closed energy storing system of two wells at least is now advocated, i.e. heat storing well and cold storing well. It shall be solved how to arrange the energy storing wells.

In order to arrange energy storing wells, two important factors must be taken into consideration, namely, variance of permeability coefficient and the original groundwater's flowing.

The variance of permeability coefficient is related with the original groundwater's flowing. The permeability coefficient in flow direction is larger than that in other direction because of the original groundwater's rinsing. It is reasonable to consider both the factors at the same time. And so, a hypothesis is raised that the permeability coefficient is identical in all directions. Then, the influence of the original groundwater flow alone should be researched.

Under the influence of the original groundwater flow, the distribution of water refilled deviates obviously from uniform circles which are at a common center, because the energy storing water mass is lengthened in the direction of groundwater flow and is flattened in the direction perpendicular to the latter. It is shaped like a pear.

Take the direction of the groundwater flow as X, the direction normal to the flow as Y. It is obviously that the energy storing wells should be arranged along the Y-coordinate to keep the interval between two of them farther than two times as the influence radius calculated. If three energy storing water wells were needed, the arranging mode is showed in Fig 2. The interval between the center of well 3 and the line connected the center of well 1 and well 2 should be more than two times as the influence radius calculated. Because well 1 and well 2 are arranged along the direction normal to the original groundwater flow, and the energy storing water mass is flattened into a shape like a pear, the actual influence radius is less than its calculated value. The rest schemes may be deduced by analogy if there are more than three energy storing water wells needed. The effect of this arrangement is shown in Fig 3 (the curves in Fig 3 and 5 stand for the stream and the arrows stand for the groundwater stream velocity vector). We can find that the stream line of both refilling wells coupled up. The area of the pumping well's stream are much larger than the area of the refilling well's. The stream in Well 2's and well 3's periphery have been interconnected, which indicates a short circuit or thermal transmission taking place between the pumping and refilling wells. This result could also be proved by the groundwater flow’s velocity vector. Therefore, in arranging of energy storing wells it is fallibility to determine the distance between wells according to thermal influence radius only. The actual distance should be much larger than the calculated influence radius for the sake of avoiding their thermal transmission.

5. The active control method

Theoretically, if the distances between wells are limited there is always infiltration coupling between wells in double well systems or multi-well systems. Utilizing the coupling effects of infiltration between wells to control the range of thermal energy water initiatively, a retrenching result in arrangement of energy storing wells may be realized. This technology is introduced by the following example of a well system’s improvement. The arrangement is shown in Fig 4. X direction is the original groundwater flow. Well 1 and well 4 are for energy storing with an interval more than two times of the influence radius. Regulating well 2 and 3 are arranged symmetrically to the mean line of energy storing wells. Similar to well 4 and well 1, regulating well 2 and regulating well 3 formed a looped cyclic system of a pumping well and a charging well. Different from the energy storing wells, the regulating wells pump and refill original underground water. While well 1 serves as a refilling well the well 2 serves as a refilling well too. Meanwhile, well 4 is pumping energy storing water and well 3 begins to pump original groundwater. In this way, well 1 and 4 form a looped pumping-refilling cyclic system and so do well 2 and 3. If the water quantity pumped and refilled by well 2 and 3 is controlled to adapt well 1 and well 4’s quantity, the distribution of flow field of well 4 and well 1 may be interfered under the coupling effects of groundwater flow. An isolation zone will be built around well 2 and 3. This isolation zone would block the heat transmission between well 1 and 4.

The key point of the technology is how to arrange the four wells reasonably and how to control the quantity of pumped and refilled water by regulating wells accurately to adapt the energy storing wells. This technology will not be realized until the above problems were solved. The effect of this arrangement is shown in Fig 5. The figure shows that an obvious coupling effect is taken between the regulating wells and energy storing wells. The refilling well 1 is “pushed” by regulating well 2 while the pumping well 4 is “pulled” by regulating well 3. The stream’s distribution shows that the streams located in the farthest periphery of each regulating well and each energy storing well are unclosed. The stream turn for 90° to the horizontal direction. It is showed that the two streams have coupled with the stream of the original groundwater but no coupled effect takes place between two energy storing wells. The groundwater stream’s velocity vector also serves as an evidence for this result. At the position of regulating well 3, the stream’s velocity vector is parallel to the vertical direction. That is to say, the direction of the stream here is same as the original groundwater flow so that coupling effects can impossible take place. It is obvious that the stream around the energy storing wells is pushed and flattened, the stream of two energy storing wells is blocked by a regulating well and so the energy storing water’s spreading is controlled efficiently.

6. Experiment and the results

The experimental system should examine the processes of flow and heat transfer, verify the exactness of the mathematical model. Hence, it must be able to simulate the practical water flow and heat transfer of the underground in aquifer. In order to imitate an infinitely great area's flow and heat transfer with a limited space, a set of experiment system to simulate the condition at the site and the analysis system for test data are equipped (Fig 6). The experiment studies the influences of natural convection to water flow and heat transfer during the refilling. The accuracy of the simulating program will be examined by the test results. On the basis of the practical data, a test of warm water refilling was performed. Warm water of $0.052M^3$, at 30□, of 1.3 L/min is charged within 40 minutes under the environment at 11□. A temperature field chart of three dimensions is made from the analysis of experimental results at the end of the refilling. Another is from the duration of heat preservation (Fig 7, 8). The accuracy of the simulating program is testified by the experimental results.

7. Conclusion

A comprehensive analyzing of aquifer's geologic characteristics ascertains that the confined aquifer is the suitable aquifer for thermal energy storage; that the storage mode should be one of same layer.

The storage duration may be as long as half a year, so that the area within the influence radius has been a thermal equilibrium state when the energy storing water is pumped out. Having analyzed the thermal equilibrium a rough thermal affecting area can be worked out under the refilling condition.

Then the rough thermal affecting area can be revised by analyzing thermal diffusion.

At last the final influential radius of a single well may be determined and the solving process is largely simplified.

Because of original groundwater's flow and infiltration, the refilled energy storing water into aquifer is no longer a uniform distribution with a center of the well's mean line. It has got an obvious distortion, that is, the energy storing water mass is lengthened in the direction of groundwater flow and is flattened in the direction perpendicular to the latter. It is shaped into a pear. The energy storing wells should be arranged in the vertical direction to the water flow so as to effectively avoid the influence of the groundwater flow.

The influence radius is enlarging as the using of the energy storing well. Theoretically, if the distances between wells are limited there is always infiltration coupling between wells in double well systems or multi-well systems. Utilizing the coupling effects of infiltration between wells to control the range of thermal energy water initiatively, a retrenching result in arrangement of energy storing wells may be realized.

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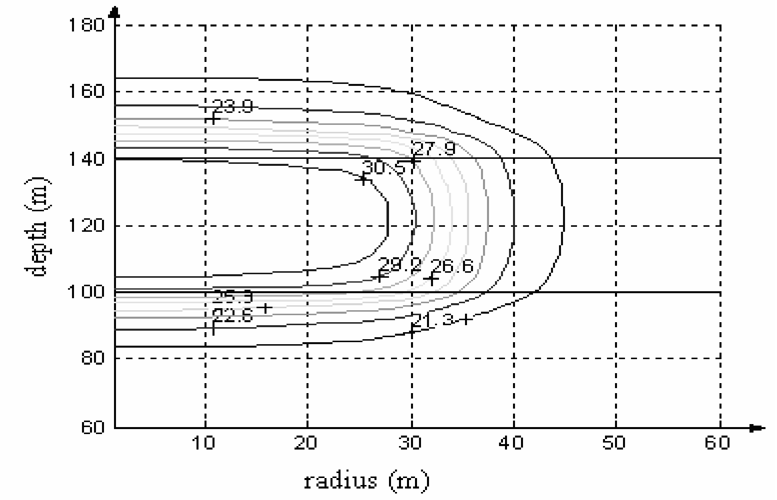

Fig. 1 aquifer's vertically temperature field

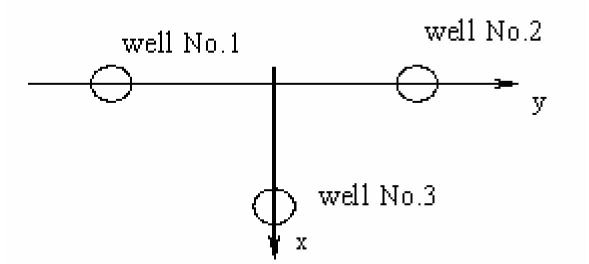

Fig. 2 arrangement of thermal energy storing wells

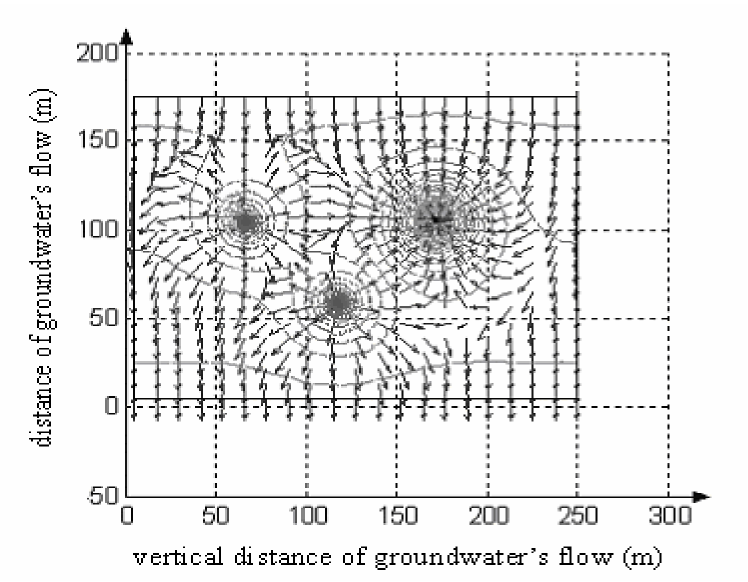

Fig. 3 the flow of three thermal energy storing wells

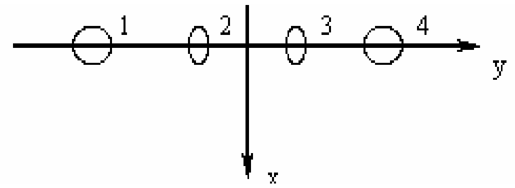

Fig. 4 arrangement of the regulating well

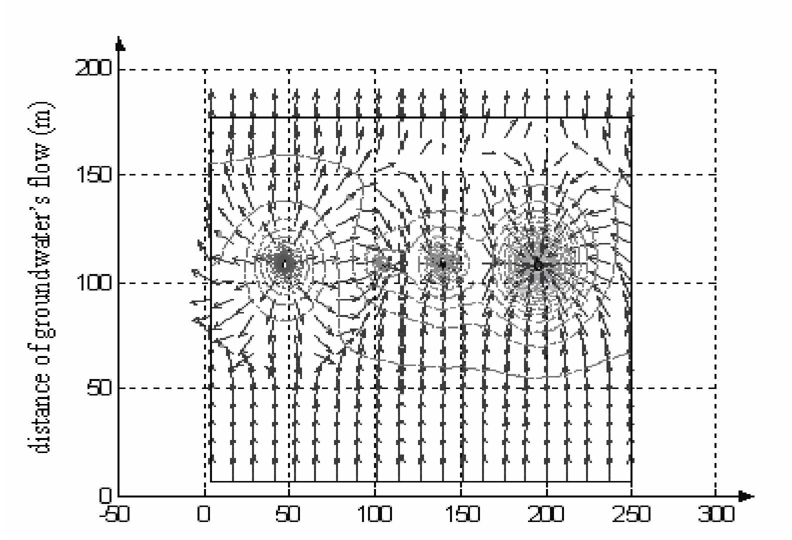

Fig. 5 effects of active control of groundwater flow

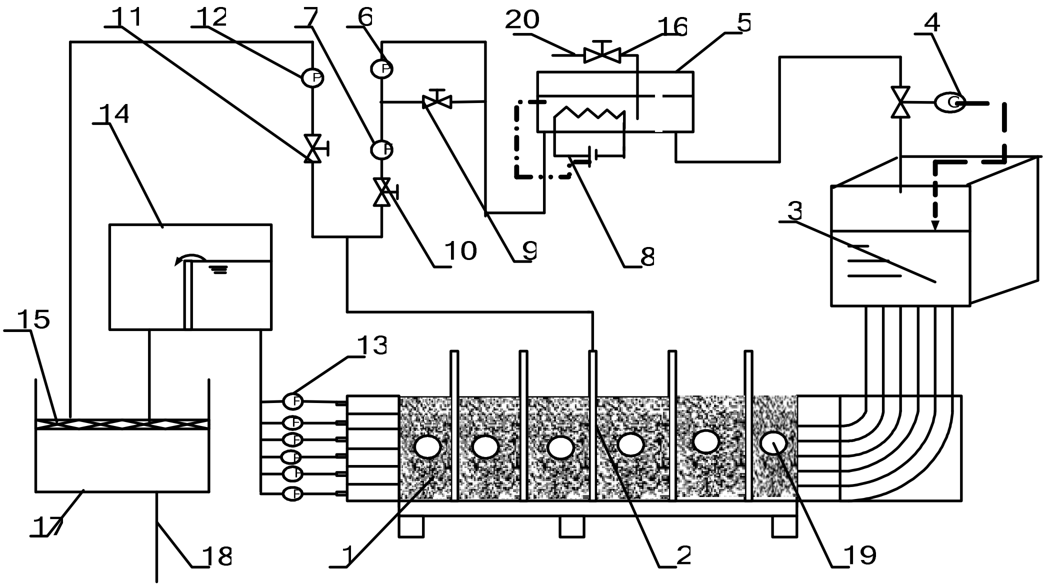

Fig.6 Structure of the experiment equipment

1. test bed’s main body
2. pre-equipped wells
3. feed-tank
4. electromagnetic shutoff valve
5. warm water-tank
6. pump
7. flow meter
8. heating equipment

9/10/11.switches

12. pump
13. flow meter
14. water storage tank
15. filtrate-net
16. control switch
17. filtrate-tank
18. vent-pipe
19. electric thermometer
20. feed-pipe

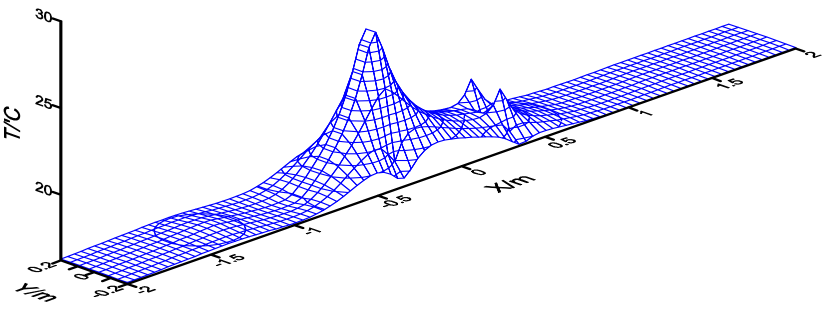

Fig.7 temperature filed （refilling finished）

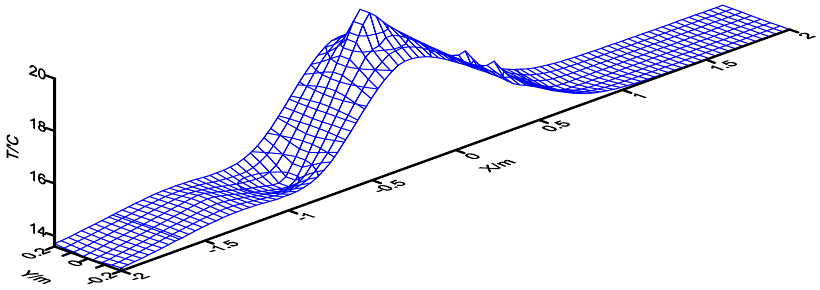

Fig.8 temperature field after heat preservation for 8h