The Selection of a Site Suitable for Aquifer Thermal Energy Storage*

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For thermal energy storage utilizing an aquifer, the selection of a suitable site is the most important process. Based on previous field experiments and analysis, further investigation to determine the most appropriate process for site selection has taken place. This paper reports the following: (1) a process for the selection of a site suitable for aquifer thermal energy storage; (2) a proposal for a new method for determining the most suitable site in terms of values of the apparent thermal diffusivity of the aquifer. This model is based on the analytical results of temperature recovery in the well after a stepwise injection of warm water into the aquifer; (3) the experimental results showed good agreement with those obtained from the method proposed above.

Key Words: Energy Storage, Heat Conduction, Thermophysical Property, Aquifer Thermal Energy Storage, Selection of Site, Thermal Recovery Factor

1. Introduction

Aquifer thermal energy storage has received worldwide attention because of its potential for large scale and long-term thermal energy storage⁽¹⁾. In a previous paper, we reported that the thermal recovery factor, defined as the ratio of the recovered to charged energy, reached 60% , and that the break-even point of construction would be 10 years, suggesting that the aquifer thermal energy storage method is a very attractive one for the future⁽²⁾. However, this method is not always applicable at a location where construction might otherwise be desirable, so the selection of a site suitable for aquifer thermal energy storage is a most important process.

As the problem of the selection of a site suitable for thermal energy storage had not been solved , we proposed a simple method for selection based on

selecting a site where groundwater does not flow⁽³⁾. This was judged from the value of the apparent thermal diffusivity of the aquifer using two wells. But this conventional method contained a serious drawback, being very expensive due to the construction of two wells. In the report that followed, a kind of comparative method using a single well, based on the standard 200 m well on the campus of Yamagata University, was proposed⁽⁴⁾. This method requires that warm water at about 20°C be injected into the well at a constant rate of 50(l/min) for 10(h) ; after injection ceases, the temperature change in the well is measured and the dimensionless temperature Ψ is obtained, as shown in Fig. 1. When the gradient of the line in the $\ln \Psi - t$ plane is less than $10^{-3}(1/h)$, a thermal recovery factor greater than 30% is guaranteed, judging from the results of the standard well. However, with this single well method, the mathematical relationship between the thermal recovery factor, and the ground structure and the groundwater velocity cannot be determined.

In this paper, a process for selecting a suitable site for aquifer thermal energy storage is proposed, based on the experience gained from field experi-

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ments. Also, a new method for determining the most suitable site by the apparent thermal diffusivity of an aquifer with a single well is proposed. The validity of our proposal was tested by scaled-down model experiments.

Nomenclature

- θ : Temperature $^{\circ}\text{C}$
 Θ : Temperature of charge $^{\circ}\text{C}$
 t : Time s
 T_0 : Period of injection s
 r : Radius in cylindrical coordinates m
 r_c : maximum radius where the temperature is affected by the injection m
 b : Thickness of the aquifer m
 a : Thermal diffusivity m^2/s
 λ : Thermal conductivity $\text{W}/(\text{m}^{\circ}\text{C})$
 c : Heat capacity of the water $\text{J}/(\text{kg}^{\circ}\text{C})$
 ρ : Water density kg/m^3
 γ : Dimensionless temperature gradient
 ξ : Ratio of temperature gradient
 $\dot{M}$: Rate of charge m/s
 f : Velocity of the current
 ϵ_{RMS} : Square root error
 Γ : Gamma function
 J_0 : 0-order, first kind of Bessel function
 J_1 : 1st-order, first kind of Bessel function
 α_n : n th root of $J_0(\alpha) = 0$

Dimensionless numbers

- Ψ : θ/Θ
 ν : $\dot{M}c\rho/(4\pi b\lambda_s)$
 X_0 : $r_c^2/(4a_sT_0)$

Fig. 1 Results of field experiments

$$R : r/r_c$$

$$T : t/T_0$$

Indices

- e : Apparent
 s : Aquifer or bead layer

2. The Selection of a Site Suitable for Aquifer Thermal Energy Storage

The estimation of the position of an aquifer suitable for thermal energy storage is so difficult, that up to now, no technique for determining the site has been perfected. In consideration of the fact that the thermal recovery factor is severely affected by the groundwater velocity, a suitable site can be approximately determined by ascertaining where the ground-water does not flow⁽⁵⁾. Reassessing our experience in the field experiments, a method for the selection of a site suitable for aquifer thermal energy storage is proposed in Fig. 2.

The site selection process is carried out in 3 stages:

2.1 First stage

(1) An aquifer runs parallel to the ground surface, as is typical of geological strata in general. However, the velocity of the groundwater is proportional to the gradient of the water head, and this is determined by the inclination of the impermeable layers of the aquifer. Therefore, as a priority, an area where the ground is flat over a wide area should be chosen.

Fig. 2 Selection of a site suitable for A.T.E.S

(2) When the groundwater in the vicinity of the site is hard a high recovery factor is anticipated as the groundwater occasionally ceases to flow in this case. An area where the rate of increase in underground temperature is sharp should be similarly considered.

2.2 Second stage

(1) Having completed the first stage, an underground map can be drawn using as many columnar maps of the existing well as possible around the proposed site.

(2) From the map, the position, size and configuration of the aquifer can be obtained. Then a region with alternate clay and gravel strata is selected as the second proposed site.

2.3 Third stage

(1) At the second proposed site, a small bore is drilled for confirmation of the strata by electric inspection and in this way the precise position of the strata can be obtained. From the map, the depth of each clay and gravel layer can be determined. The alternate layer structure is usually excellent for energy storage because the clay layers converge downstream enclosing the sand or gravel, and therefore water in the gravel layer can-not flow out.

(2) The apparent thermal diffusivity of the aquifer is measured, to confirm that the thermal recovery factor is good. The analytical and experimental results necessary for the measurement of the apparent thermal diffusivity of the aquifer are shown in the following section.

3. Analysis of the Temperature Response in the Aquifer

Analysis of the temperature response in the aquifer is very difficult because the configuration of the actual strata is usually very complex. For this reason, a simplified model was introduced for the purpose of analysis, and is given as follows:

(1) The aquifer is a two-dimensional parallel plane with thickness b , confined both above and below by the impermeable strata.

(2) The flow in the aquifer is Darcy and centrifugal around the charge well.

(3) Heat loss through both the top and bottom of the strata is negligible.

3.1 Temperature recovery after the stepwise charge has ceased.

From time $t = -T_0$ to $t = 0$, warm water kept at constant θ is charged at a constant rate $\dot{M}$ into the aquifer, initially kept at a constant $\theta = 0$, via the central well, where the centre of the well is taken as the origin of the coordinate r (see Fig. 10). After the charge has stopped, the temperature recovery is measured from $t = 0$ to $t = T_0$. Taking the dimension-

less temperature Ψ as θ/θ_0 , and dimensionless time T as t/T_0 , the energy equation, the initial condition, the boundary conditions and the solution are given respectively as follows:

(1) When $-1 < T < 0$,

$$\text{Energy equation: } \frac{\partial \Psi}{\partial T} = a_s T_0 \nabla^2 \Psi - \frac{T_0 \dot{M} c \rho}{2\pi b (c \rho)_s r} \nabla \Psi \quad (1)$$

$$\text{Initial condition: } \Psi = 0 \quad (2)$$

$$\text{Boundary condition: } \Psi = 1 \text{ at } r = 0, \quad \Psi = 0 \text{ when } r \rightarrow \infty \quad (3)$$

$$\text{Solution: } \Psi = 1 - \frac{1}{\Gamma(\nu)} \int_0^x \exp(-u) u \, du \quad (4)$$

$$x = \frac{r^2}{4a_s T T_0} \quad (5)$$

$$\nu = \frac{\dot{M} c \rho}{4\pi b \lambda_s} \quad (6)$$

(2) When $0 < T < 1$

$$\text{Energy equation: } \frac{\partial \Psi}{\partial T} = a_e T_0 \nabla^2 \Psi \quad (7)$$

$$\text{Initial condition: } \Psi = \Psi_0 \quad (\text{the temperature when the charge has stopped}) \quad (8)$$

$$\text{Boundary condition: } \Psi = 0 \text{ at } r = r_c \quad (9)$$

r_c , although being mathematically infinite, is approximated as the critical radius when there is no temperature change during the time period $-1 < T < 0$. The critical radius is obtained easily within the time conservative range $-2 < T < 0$. The relation between the dimensionless parameter ν and x_0 is obtained numerically by making the left side of Eq. (4) equal to zero and shown in Fig. 3. As shown in this figure, x_0 is obtained from ν where ν is calculated using Eq. (6) with charge rate $\dot{M}$, injection period T_0 , thickness of aquifer b , thermal conductivity λ_s , and thermal diffusivity of the aquifer a_s , λ_s and a_s being estimated for an aquifer with a filler of sand, gravel and water.

Fig. 3 The relation between the dimensionless charge ν and dimensionless radius x_0

Then the critical radius r_c is obtained from the formula $r_c = 2\sqrt{(2T_0 a_s x_0)}$ from Eq. (5). At this point, using the dimensionless radius R , the solution is obtained as follows:

$$\Psi = \Gamma \frac{2}{(\nu)^2} \sum \frac{J_0(R\alpha_n)}{\alpha_n J_1^2(\alpha_n)} \exp\left(\gamma_n \cdot \frac{t}{T_0}\right) \times \int_0^1 R J_0(R\alpha_n) \Psi_0 dR \quad (10)$$

where

$$\gamma_n = -a_s \frac{\alpha_n^2}{r_c^2} T_0$$

and Ψ_0 is the initial temperature field, given as follows:

$$\Psi_0 = 1 - \frac{1}{\Gamma(\nu)} \int_0^{x_0} \exp(-u) u du \quad (11)$$

$$x_0 = \frac{r_c^2}{4a_s T_0} \quad (12)$$

$$\nu = \frac{Mc\rho}{4\pi b\lambda_s} \quad (13)$$

α_n is the n -th root of $J_0(\alpha) = 0$

After the charge ceases, the temperature field in the aquifer is given by the infinite series of the transcendental function as shown in Eq. (10). As an example of a numerical solution, the temperature field in the aquifer is shown in Fig. 4 for the case of $\nu = 2.63$. After the charge stopped, the temperature level de-

Fig. 4 The dimensionless-temperature in the aquifer after the charge stopped

Fig. 5 Several terms of the infinite series of the dimensionless-temperature with respect to the time elapsed (from 1st to 5th terms)

creased and spread outwards from the well. Nevertheless, the temperature field did not reach the critical radius r_c within the time range $0 < T < 1.0$.

By contrast, several terms of the infinite series are shown in Fig. 5 with respect to the time elapsed. The subscripts 1, 2, 3, ..., show the number of the terms. The first term is not always sufficient for approximating the whole series. In the case where $\nu = 2.63$, the sum of the first three terms is greater than the sum of the higher terms. The first 10 terms are shown in Table 1. From the table, we can see that the terms from the 7th onwards are negligible for practical use because within the time range $0.5 < T < 1.0$, they are all less than 0.001. Hereafter, the summation of the first 10 terms is regarded as the infinite series for the conservative time range $0.5 < T < 1.0$.

Taking the natural logarithm of the dimensionless temperature, a graph of $\ln \Psi - T$ is shown in Fig. 6. It shows that $\ln \Psi$ decreases linearly in accordance with the time elapsed. Within the range of the dimensionless time $0.5 < T < 1.0$, the curve is approximated by the straight line $\alpha T + \beta$. The maximum error between the straight line and $\ln \Psi$ is given by the square root mean value $\varepsilon_{RMS} = \sqrt{\sum (\alpha T + \beta - \ln \Psi)^2 / n}$.

Table 1 Results of the numerical calculation of first 10th terms

$\nu = 2.63$						
t/T_0	0	0.2	0.4	0.6	0.8	1.0
term						
1	0.406	0.400	0.395	0.390	0.384	0.379
2	0.537	0.500	0.465	0.433	0.403	0.375
3	0.243	0.204	0.171	0.143	0.120	0.100
4	-0.041	-0.030	-0.021	-0.015	-0.011	-0.008
5	-0.103	-0.061	-0.036	-0.021	-0.013	-0.007
6	-0.050	-0.023	-0.011	-0.005	-0.002	-0.001
7	-0.006	-0.002	-0.001	0.000	0.000	0.000
8	0.006	0.001	0.000	0.000	0.000	0.000
9	0.004	0.001	0.000	0.000	0.000	0.000
10	0.002	0.000	0.000	0.000	0.000	0.000

Fig. 6 The natural logarithm of the dimensionless temperature with respect to the time elapsed

Because Ψ is a function of ν , ϵ_{RMS} is also a function of ν . The results of the numerical calculation are presented in Fig. 7, and this shows that ϵ_{RMS} has a minimum value when $\nu=2.03$. This value is called ν_0 and is the dimensionless optimum charge.

Under the optimum condition where a linear approximation is the best estimation, the gradients obtained from $\ln \Psi - T$ and $\ln \Psi_1 - T$ are γ and γ_1 respectively, as shown Fig. 8. It is clear from Eq. (10) that the ratio of the two gradients $\xi = \gamma/\gamma_1$ is a function of the dimensionless charge volume ν with a correlation of $\gamma_1 = -a_e \alpha_1^2 T_0 / r_c^2$. The value of ξ , obtained numerically, is shown in Fig. 9 as a function of ν .

3.2 Determination of the capacity of the aquifer for thermal energy storage

Against a given ν , the following relation is obtained from the linear gradient of $\ln \Psi - T$ and the ξ in Fig. 9.

$$a_e = -\gamma r_c^2 / (\xi \alpha_1^2 T_0) \quad (14)$$

where α_1 is the first root of $J_0(\alpha) = 0$ ($\alpha_1 = 2.4048$)

This means that the apparent thermal diffusivity of the aquifer can be obtained by the following procedure: i) the warm water kept at a constant tempera-

ture is charged stepwise; ii) measurement of the temperature recovery of the well within the time interval $0.5 < T < 1.0$, after the charging ceased, leads to a logarithmic gradient γ of the dimensionless temperature; iii) ξ is obtained corresponding to ν in Fig. 9; iv) a_e is obtained from equation (14).

As mentioned before, if the velocity of the groundwater is too fast, a high value recovery factor for thermal energy storage cannot be expected; in this case, the apparent thermal diffusivity is 4~10 times greater than the case when water does not flow in the usual filler of sand, gravel and water. On the contrary, if the apparent thermal diffusivity in the field situation is of the same order as that in the model situation using the usual filler, it may be concluded that the groundwater is probably still and a high value for the thermal recovery factor can thus be expected.

The previous comparative method for determining the capacity for thermal energy storage using the logarithmic temperature gradient only corresponded to the judging method using the combined parameters of the apparent thermal diffusivity and operative conditions, i.e. T_0 , $\dot{M}$, Θ and so on.

4. Model Experiment

4.1 Experimental Apparatus

The geological structure of an aquifer is usually so complex that occasionally, even the boundaries of the strata cannot be determined. For confirmation of the confidence with which the site can be determined as proposed in the previous section, model experiments using an artificial aquifer where the strata are known, are superior to field experiments. The experimental aquifer apparatus is shown in Fig. 10. The artificial aquifer was constructed in a concrete pool of size 2700 × 4700 mm. The glass bead layer was 350 mm thick, and the mean diameter of the individuals beads was 1.7 mm. This bead layer was sandwiched top and bottom with layers of bentonite, 500 mm and 200 mm thick respectively, the impervious layers. At

Fig. 7 The results of numerical calculation of ϵ_{RMS} with respect to

Fig. 8 Situation of the gradients obtained from $\ln \Psi$ and $\ln \Psi_1$

Fig. 9 The value of ξ as a function of ν

the center of the model a charge well ⑦ made of a hard vinyl pipe of 50 mm diameter, and 56 observation wells were constructed. The charge well had slit-type strainer for the charge and backwash operations at the bead layer. Fourteen equidistant thermocouples (C-C) were set in the charge well for temperature measurement. The observation well had the same type of strainer as the charge well in the bead layer and inside the tube was an acrylic float on which a thin stainless steel pipe was attached for the measurement of the water level by the leveler, fixed at the position shown in Fig. 11.

The experiments proceeded as follows. Water was supplied at a constant rate to the side-pocket of the concrete pool ② from the overflow tank ① through the flow meter *F*, creating a water head gradient in the bead layer. The supplied water flowed

Fig. 10 The experimental aquifer apparatus

Fig. 11 Observation well

through the bead layer ③ into the opposite side-pocket ④ where the underwater pump ⑤ pumped the water out automatically by the action of the level switch. This imitates the steady state ground water flow the velocity of which is regulated by the amount of the water supplied from the overflow tank.

Under this steady flow, imitating the natural groundwater flow, hot water, heated by the heater ⑥ was charged stepwise into the central well ⑦. After the charge had stopped, the temperature recovery of the well was measured by a digital recorder ⑧, enabling the calculation of the apparent thermal diffusivity a_e of the modeling aquifer using Eq.(14).

4.2 Results of the experiment

As an example, the temperature recovery of the well is shown in Fig. 12, measured under the conditions $T_0=20$ min, $\dot{M}=0.757$ l/min, $\theta=32.6^\circ\text{C}$, and $f=0$ m/s. Within the time interval $0.5 < T < 1.0$, the logarithmic dimensionless temperature $\ln \Psi$ decreased linearly. Using the gradient γ of the line in Fig. 12 and ξ in Fig. 9, a value for apparent thermal diffusivity a_e of $1.01 \times 10^{-6} \text{ m}^2/\text{s}$ was obtained, which was very similar to that in table (6) for the glass bead filler saturated with water.

The apparent thermal diffusivity obtained by changing the flow velocity of the groundwater flow is

Fig. 12 Data of the temperature recovery of the well

Fig. 13 The apparent thermal diffusivity of changing the flow velocity of the groundwater

shown in Fig. 13. It shows that the apparent thermal diffusivity increases in proportion to the velocity of the groundwater when it flows very slowly, i.e. less than 0.15 m/s. In this situation, the following relation is given by a first approximation.

$$\begin{aligned} a_e &= a_s + zf \\ z &= \frac{c\rho}{(c\rho)_s} \frac{\nabla \theta}{\nabla^2 \theta} \end{aligned} \quad (15)$$

5. Conclusions

Field experiments on a method for thermal energy storage utilizing an aquifer have been conducted in our laboratory over a long period. During these investigations, a new physical fact was noticed: the capacity of the aquifer for thermal energy storage can be estimated from the speed of the temperature recovery of the well after hot water has been charged in step-wise. In this paper, our previous experiences were reassessed and new analytical and experimental investigations were carried out, leading to the following results:

- (1) A new process for locating a suitable place for thermal energy storage utilizing an aquifer was proposed.
- (2) A new method for determining the aquifer thermal energy storage capacity was investigated, by means of the apparent thermal diffusivity of the

aquifer; this was measured by making use of the analytical results of the temperature recovery of the well after hot water had been charged into the well in a step-wise manner.

(3) The method for determination proposed above was confirmed by scaled-down simulation experiments.

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