Title
NUMERICAL MODELING OF AQUIFER THERMAL ENERGY STORAGE

Authors
Tsang, C.F.
Doughty, C.
Kincaid, C.T.

Publication Date
1982-08-01

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

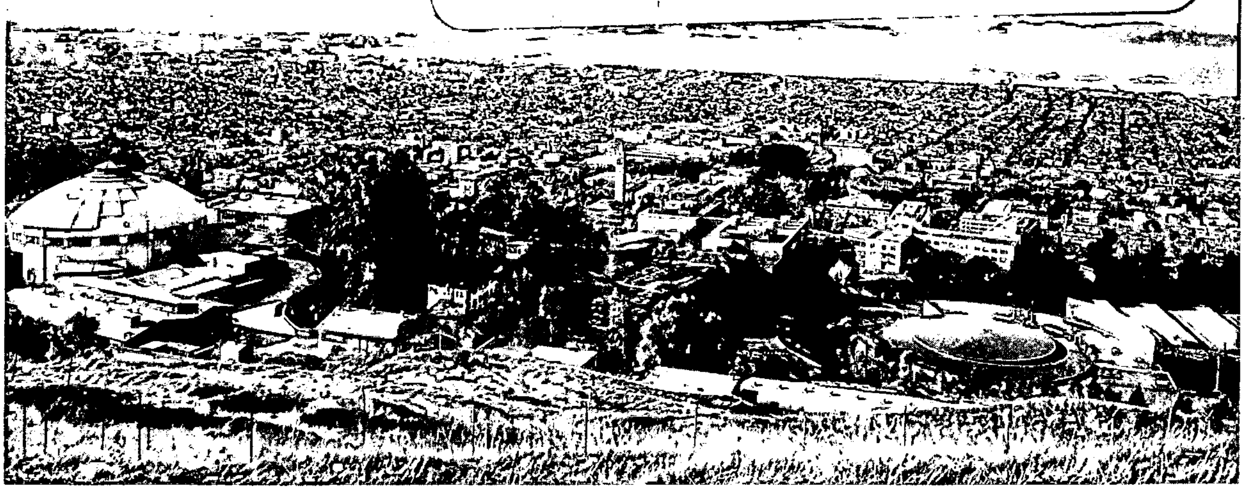
EARTH SCIENCES DIVISION

Presented at the Energy Storage Contractors' Review Meeting, Crystal City, Arlington, VA, August 23-26, 1982

NUMERICAL MODELING OF AQUIFER THERMAL ENERGY STORAGE

C.F. Tsang, C. Doughty, and C.T. Kincaid

August 1982



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

NUMERICAL MODELING OF AQUIFER THERMAL ENERGY STORAGE

C. F. Tsang and C. Doughty
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

C. T. Kincaid
Pacific Northwest Laboratory
Richland, Washington 99352

Introduction

During 1981 and 1982, Auburn University has been performing a three-cycle ATES field experiment in Mobile County, Alabama. Details of the experiment are described elsewhere in this volume. Concurrent with the first two cycles (59°C and 82°C), Lawrence Berkeley Laboratory (LBL) did numerical simulations based on field operating conditions to predict the outcome of each cycle before its conclusion. Prior to the third cycle, a series of numerical simulations were made to aid in the design of an experiment that would yield the highest recovery factor possible.

First-Cycle Prediction

During the first cycle, 25,000 m^3 of water at an average temperature of 59°C was injected over a period of one month into a 21 m-thick aquifer. It was then stored for one month and subsequently produced. The injected water was obtained from a supply well perforated in the same aquifer 240 m away from the injection/production well. LBL was provided with the basic geological, well-test, injection flowrate, and injection temperature data, as well as the planned production flow rate.

The well-test data and geological information were studied and analyzed to obtain reservoir parameters and their range of uncertainty. The parameters used in our numerical simulation are listed in Table 1. Since the supply well is 240 m from the injection/production well and the thermal radius was calculated to extend only about 25 m, it was decided that a radial calculation mesh would be adequate. Based on the flow rates and injection temperature provided, we simulated the experiment using the numerical model PT (formerly called CCC) developed at LBL. The calculated production temperature is presented as curve A in Figure 1, where the experimental result is also plotted. The experimental results were made known to us after we completed and presented our results. The predicted energy recovery factor is 0.620 compared to the experimental value of 0.552. This agreement is satisfactory.

First Cycle: Detailed Comparison Between Theory and Experiment

Next, a series of parameter studies were made comparing the experimental and calculated temperature fields at various times during the first cycle. These studies led us to hypothesize that the aquifer is vertically stratified into three layers, the middle layer (5 m thick) having a permeability 2.5 times that of the upper and lower layers.

Using this model, the first-cycle recovery factor was calculated to be 0.579, calculated production temperature is shown as curve B in Figure 1. Apparently the layered structure of the aquifer noticeably lowers the recovery factor. This is significant because layering is difficult to detect through conventional well-test analysis.

Table 1. Parameters used in the first-cycle prediction numerical simulation.

Thermal conductivity	Aquifer	2.29 J/m.s.°C
	Aquitard	2.56 J/m.s.°C
Heat capacity of rock		1.81×10^6 J/m^3.°C
Aquifer horizontal permeability		63 darcies
Aquifer vertical to horizontal permeability ratio		1:7
Aquitard to aquifer permeability ratio		10^{-5}
Porosity	Aquifer	0.25
	Aquitard	0.35
Storativity	Aquifer	6×10^{-4}
	Aquitard	9×10^{-2}

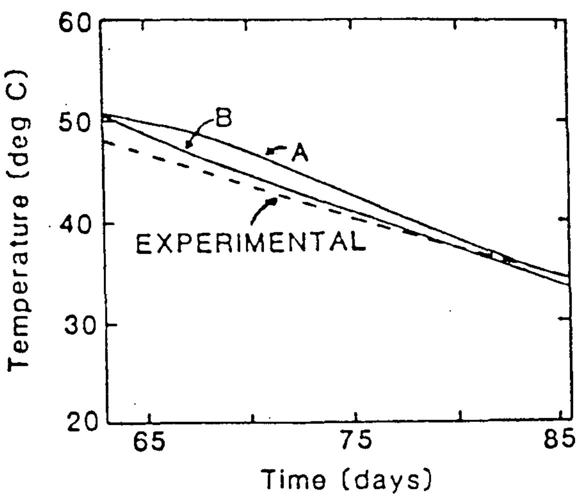


Figure 1. First-cycle Production Temperature.

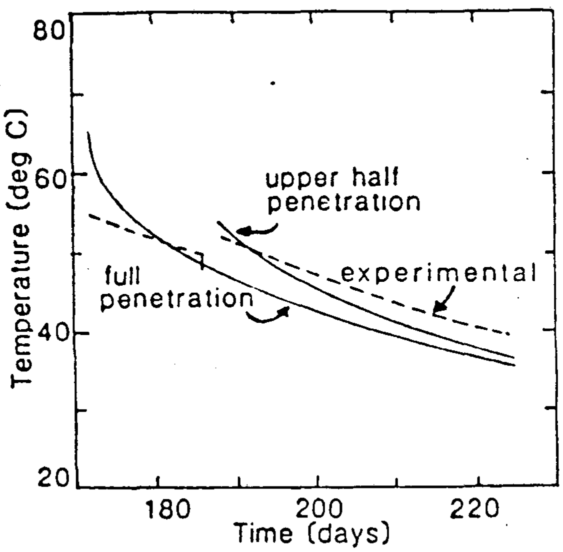


Figure 2. Second-cycle Production Temperature.

Second-Cycle Prediction

The procedure is similar to the first cycle prediction. Only the injection flow rate, temperature history, storage period, and expected average production flow rate were made known to us. The three-layered aquifer model described in the previous section was used for the calculation. Water at an average temperature of 82°C was injected over a period of about 4.5 months. The variable, experimental injection flow rates and temperatures were averaged into five segments for the numerical simulation. The total volume injected, about 58,000 m^3 was considerably larger than the volume injected during the first cycle; hence the thermal radius extended farther than in the first cycle (to about 38 m). However, this distance is still small enough compared to the distance to the supply well to justify using a radial calculation mesh. After injection, the hot water was stored for 34 days.

The simulation of the original production plan--to produce all the injected water through the fully penetrating well screen that had been used throughout the experiment--was carried out, using a constant fluid flow rate of 200 gpm. The calculated recovery factor is 0.406 and the production temperature is shown in Figure 2.

However, this production plan was changed after two weeks of production. At that time the well was shut down and modified to produce fluid from only the upper half of the aquifer; then production was resumed. This scenario was again simulated using a constant flow rate of 200 gpm. The calculated recovery factor is 0.434; the production temperature is shown in Figure 2. After the second-cycle calculation was completed the experimental results were made known to us: the reovery factor is 0.452, the production temperature is shown in Figure 2. Comparisons between the experimental and calculated temperature fields in the aquifer throughout the second cycle show acceptable agreement.

Second-Cycle Optimization Studies

The recovery factor improvement of about 3% may have been small because the lower part of the modified well screen intersected the high-permeability layer of the aquifer and water may have been selectively produced from this cooler region rather than from the warmer upper region of the aquifer. In order to study the effects of different injection/production schemes, a series of numerical simulations based on the second cycle were run employing different well-screen intervals. Each simulation used a simplified injection history consisting of one constant injection flow rate and temperature. Table 2 summarizes the optimization simulations. Collectively, these results indicate that although buoyancy flow is strong in the aquifer, an improvement of almost 10% can be achieved by selective injection and production schemes.

Table 2. Second-Cycle Summary.

	Well-Screen Interval		
	Injection	Production	ε
Experiment	full	full for 2 weeks upper half thereafter	.452
Prediction	full	full	.406
	full	full for 2 weeks upper half thereafter	.434
Optimizations			
A	full	full	.407
B	full	upper 40%	.466
C	full	upper 20%	.496
D	lower half	upper half	.494
E	upper 20%	upper 20%	.504

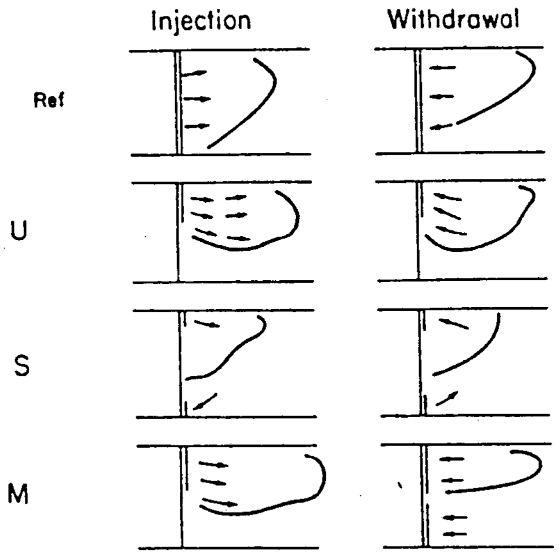


Figure 3. Schematic drawing of the flow fields during injection and withdrawal for the third-cycle design studies.

Third-Cycle Design Studies

Recent work involves assisting Auburn University in its planning for the third-cycle experiment. Alternative injection and production schemes have been studied to maximize the recovery factor for a three-month cycle with constant injection flow rate of 112 gpm and temperature of 82°C. Making use of the knowledge gained from the first- and second-cycle simulations, that buoyancy flow is strong, three approaches have been taken. These are shown schematically in Figure 3, along with a reference case that uses full penetration during injection and production. These three approaches are explained as follows:

1. Simply inject into and produce from the upper portion of the aquifer where most of the hot water would naturally flow because of buoyancy effects (labeled U).

2. Attempt to maintain a compact shape for the injected fluid. Buoyancy flow is counteracted by pumping from the bottom of the aquifer as hot water is injected into the top (labeled S).

3. Inject into the upper portion of the aquifer. Then, while producing from the upper portion, produce (and discard) colder water from the lower portion of the aquifer. Thus the colder water will not be pulled into the upper well where it would lower production temperature (labeled M).

Table 3 summarizes the results of the numerical simulations. For a cycle consisting of one month each of injection, storage, and production, the maximum recovery factor is about 0.52, representing an improvement of about 0.12 over the reference case. However, if the three-month cycle is altered so that two months of injection are followed immediately by one month of production (at twice the injection flow rate) hence doubling the storage volume, a recovery factor of about 0.66 is possible. Hence for this system, the volume of fluid injected is as important as the manner in which it is injected and produced.

Table 3. Third-Cycle Design Studies. T_1 = 82°C, Q = 112 gpm.

I. 1 month each, injection, storage, production V = 18,300 m^3

Case	Well Screen Interval: Injection	Well Screen Interval: Production	ε
Ref.	Full	Full	0.404
U1	Upper 40%	Upper 40%	0.448
U2	Upper 40%	Upper 20%	0.501
S1	Upper 20% Lower 20%	Upper 20%	0.516
S2	Upper 20% Lower 20%	Upper 20% Lower 20%	0.487
M1	Upper 40%	Upper 40% Lower 55%	0.500
M2	Upper 40%	Upper 20% Lower 55%	0.521

II. 2 months injection, 1 month production. V = 36,600 m^3, $Q_p = 2Q_i$

Case	Injection	Production	ε
U1-2	Upper 40%	Upper 40%	0.609
M1-2	Upper 40%	Upper 40% Lower 55%	0.629
M3-2	Upper 40%	Upper 40% Lower 20%	0.631
M4-2	Upper 40%	Upper 20% Lower 20%	0.661

Conclusion

The successful prediction of the first- and second-cycle energy recovery factors has demonstrated that the main physical processes occurring in the Mobile ATES field are probably well understood and can be properly simulated by the numerical model PT. The third-cycle design studies consider a substantial number of alternative injection/production schemes. Results have been transmitted to Auburn University for consideration in their decisions concerning the third-cycle experiment. This demonstrates the value of numerical modeling. If one were to experimentally carry out all the alternative designs, an order of magnitude increase in budget and time would be required.

Acknowledgements

This work was supported by the Assistant Secretary of Conservation and Solar Energy, Office of Advanced Conservation Technology, Division of Thermal and Mechanical Storage Systems of the U. S. Department of Energy under Contract DE-AC03-76SF00098. This report represents work performed within the Seasonal Thermal Energy Storage Program managed by Pacific Northwest Laboratory.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720