TWO-DIMENSIONAL FLUID AND THERMAL ANALYSIS OF DRY POROUS ROCK RESERVOIRS FOR CAES

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ABSTRACT

The analysis of the hydrodynamic and thermodynamic response of a Compressed Air Energy Storage (CAES) dry porous media reservoir subjected to daily air mass cycling is described. The analysis is based upon a numerical computer model that uses a finite difference method to solve the two-dimensional (r-z) conservation equations for the transport of mass, momentum, and energy in the below ground system. The investigation quantifies the behavior of those parameters that enter the model by virtue of inclusion of the vertical dimension. The topics that were evaluated were the wellbore heat transfer and the pressure and temperature response of the reservoir. The wellbore heat transfer was evaluated with respect to insulation, preheating (bubble development with heated air), and air mass flow rate. The wellbore heat transfer reduces thermal energy recovery while offering the advantage that the temperatures and thermal cycling at the reservoir were reduced. The most severe thermal cycling occurred in the wellbore near the earth surface. The pressure and temperature responses of the reservoir were found to be largely dependent on the producing length of the wellbore within the porous zone. Reduced producing lengths resulted in increased reservoir pressure losses as well as non-uniform temperature distributions. Other reservoir parameters that were evaluated that had less significant effects were anisotropic permeability and stratified permeability, heat losses to the vertical boundaries, and natural circulation.

INTRODUCTION

The analysis of the hydrodynamic and thermodynamic response of CAES porous media reservoirs subjected to daily air mass cycling is intended to provide design guidelines for the efficient and stable operation of the air storage reservoir. Previous investigations performed at PNL^(1,2) have been based on one-dimensional (radial) modeling. Several parameters were subsequently identified that required two-dimensional (radial, vertical) modeling to be able to quantify their effect on reservoir performance. These parameters included heat transfer between the wellbore and the caprock and overburden, heat transfer between the porous zone and its vertical boundaries, natural circulation in the porous zone, anisotropic and stratified material properties (specifically, permeability) and the producing length of the wellbore. The two-dimensional model and the analysis of these parameters is the subject of this paper.

THEORETICAL DEVELOPMENTBASIC ASSUMPTIONS AND GOVERNING EQUATIONS

The important basic assumptions that were applied to this analysis are:

- The fluid and solid phases are in local thermal equilibrium.
- The transport of mass, momentum, and energy occurs in the radial and vertical directions.
- The reservoir and the air are dry.
- The Darcy equation for low velocity flow is applied.

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Additional assumptions are described in a topical report to be issued by PNL. The application of these assumptions results in the following set of equations that describe the transport of mass, momentum and energy in the reservoir.

- Conservation of mass

$$\frac{\partial}{\partial t} (\phi \rho) + \frac{1}{r} \frac{\partial}{\partial r} (r \phi \rho u) + \frac{\partial}{\partial z} (\phi \rho w) = 0 \quad (1)$$

- Conservation of momentum in the radial direction

$$\left(\frac{\mu \phi}{k_r \rho} \right) (\phi \rho u) = -\phi \frac{\partial P}{\partial r} \quad (2)$$

- Conservation of momentum in the vertical direction

$$\left(\frac{\mu \phi}{k_z \rho} \right) (\phi \rho w) = -\phi \frac{\partial P}{\partial z} + \phi \rho g_z; \text{ and} \quad (3)$$

- Conservation of energy

$$\frac{\partial}{\partial t} \left\{ (1-\phi) \rho_s C_s T + \phi \rho C_v T \right\} + \frac{1}{r} \frac{\partial}{\partial r} (r \phi \rho u C_p T) + \frac{\partial}{\partial z} (\phi \rho w C_p T) - \frac{1}{r} \frac{\partial}{\partial r} (r K_r \frac{\partial T}{\partial r}) - \frac{\partial}{\partial z} (K_z \frac{\partial T}{\partial z}) = 0 \quad (4)$$

A definition of nomenclature is given in Table 1.

BOUNDARY CONDITIONS

The reservoir geometry used in this study is shown in Fig. 1 where the region of influence of a single well is shown as a vertical cylinder with the wellbore at the center. The applicable regions of the overburden, caprock, porous rock and basement rock are shown. The producing length of the wellbore is the section of the wellbore in the porous zone through which air can pass. At the wellhead the mass flow rate is continuously specified. During the reservoir charge cycle the temperature is specified. During reservoir discharge or when the reservoir is closed, the temperature at the wellhead is obtained from local equilibrium conditions. The outer radial boundary of the single well reservoir is insulated to the transport of mass and energy. The vertical boundaries of the porous zone are insulated to the transport of mass. The earth surface and the bottom of the basement rock are insulated to the transport of energy. The schedule for weekly air mass cycling is depicted in Fig. 2.

REFERENCE CONDITIONS

The foundation of the analysis is a set of reference conditions for the reservoir geometry, material properties and operating conditions. The values given to these parameters are provided in Table 2. Unless otherwise specified, these values apply throughout the discussion of results.

SOLUTION

A detailed outline of the solution method of the governing equations will be provided in a topical report to be issued by PNL. Briefly, the solution is achieved with a numerical computer model which is based on finite difference techniques.

ANALYSIS AND RESULTS

The development of the multi-dimensional numerical model has provided the capability to investigate several important aspects of reservoir behavior that were previously beyond the consideration of the available one-dimensional models. The additional phenomena that could be evaluated were generally related to either the wellbore heat transfer problem or to those parameters that introduced vertical fluid and thermal perturbations in the porous zone.

TABLE 1. Nomenclature

C_s	- Heat capacity of rock
$C_D (C_V)$	- Constant pressure (constant volume) specific heat of air
g_z	- Gravitational acceleration in vertical direction
$k_r (k_z)$	- Permeability in radial direction (vertical direction)
$K_r (K_z)$	- Effective thermal conductivity of porous rock in radial direction (vertical direction)
P	- Pressure of air
r	- Radial coordinate
t	- Time
T	- Temperature
u	- Radial velocity of air
w	- Vertical velocity of air
z	- Vertical coordinate
ϕ	- Porosity
$\rho (n_s)$	- Density of air (rock)
ν	- Viscosity of air

TABLE 2. Reference Reservoir Conditions

Parameter	Reference Value	
Geometry		
Reservoir Depth	518.2 m	(1700 ft)
Vertical Thickness	30.5 m	(100 ft)
Reservoir Diameter	121.2 m	(400 ft)
Well Diameter	0.17 m	(7 in)
Completion Length	30.5 m	(100 ft)
Properties		
Porosity	20%	
Permeability	500 md	
Rock Thermal Conductivity	$2.16 \frac{W}{m \cdot ^\circ C}$	$(1.25 \frac{8tu}{hr \cdot ft \cdot ^\circ F})$
Rock Thermal Capacity	$2.62 \frac{MJ}{m^3 \cdot ^\circ C}$	$(39.1 \frac{8tu}{ft^3 \cdot ^\circ F})$
Operating Conditions		
Nominal Pressure	5070 kPa	(50 atm)
Air Flow Rate		
Injection	$5.45 \frac{kg}{sec}$	$(12.0 \frac{lbm}{sec})$
Extraction	$7.17 \frac{kg}{sec}$	$(15.8 \frac{lbm}{sec})$
Percent of Air Cycled	12%	
Injection Temperature	232°C	(450°F)
Earth Surface Temperature	21 °C	(70°F)
Geothermal Gradient	0.0017°C/m	(0.001°F/ft)
Initial Reservoir Temperatures Determined by Geothermal Conditions		

Fig. 1. Geometry for Two-Dimensional Analysis

Fig. 2. Reference Weekly Reservoir Pressure Cycle

WELLBORE HEAT TRANSFER

Heat losses between the wellhead and the reservoir can have a significant impact on thermal energy recovery, thermal cycling, and thermal distributions. The parameters that were identified as having an impact on the wellbore heat transfer included wellbore insulation, preheating, air storage volume and reservoir depth. Wellbore insulation involves the modeling of an annular region of insulating material around the wellbore. Preheating refers to the heating of the underground system by injecting heated air during bubble development. The air storage volume and reservoir depth will affect the optimum air mass flow rates and, therefore, the thermal energy entering the underground system. The depth also establishes the length over which the heat transfer may occur. To characterize the thermal response for these parameters, six cases were defined for analysis. These are outlined in Table 3. Each case was simulated for 1-yr of air mass cycling. Only the results for the insulated and preheated conditions are provided here. The cases involving storage volume and depth (cases 5 and 6, respectively) basically only involve the rate of thermal energy entering the underground system. This will affect the magnitude of the results compared to the reference conditions but the same characteristic behavior is observed. Details of the analysis of these parameters is left to the topical report to be issued by PNL.

TABLE 3. Parametric Cases for Wellbore Heat Transfer Analysis

Case	Initial Thermal Conditions	Wellbore Insulation	Reservoir Depth (m) (ft)	Reservoir Thickness (m) (ft)	Other Conditions
1	Geothermal	No	518.2 (1700)	30.5 (100)	Reference
2	Preheated	No	518.2 (1700)	30.5 (100)	
3	Geothermal	Yes	518.2 (1700)	30.5 (100)	
4	Preheated	Yes	518.2 (1700)	30.5 (100)	
5	Geothermal	No	518.2 (1700)	61.0 (200)	Double Air Mass Flow Rates
6	Geothermal	No	1036.3 (3400)	30.5 (100)	Double Air Mass Flow Rates

A summary of the results for the thermal energy recovery is shown by Fig. 3. The results are compared with the results obtained by the one-dimensional model which employed essentially the same reservoir and operating conditions. The one-dimensional result essentially represents, for comparative purposes, a perfectly insulated wellbore.

Thermal cycling of the air in the wellbore during the first week of simulated reservoir operation is shown in Fig. 4 for the reference conditions. Thermal development doesn't change the shape of the cycles although the amplitude of the cycles diminishes and the temperatures generally increase in time.

Insulation

The insulation is represented by a 10.2 cm (4.0 in) annulus with an I.D. of 20.3 cm (8.0 in). The conductivity of the insulation was 0.216 W/m-°C (0.125 Btu/hr-ft-°F). The volumetric heat capacity of the insulation ($\rho_i C_i$) was 0.724 MJ/m³-°C (10.8 Btu/ft³-°F).

Thermal cycling of the air in an insulated wellbore is shown in Fig. 5 for the first week of simulated reservoir operation. The interesting point of this result is that the thermal cycling of the air in the wellbore is actually greater for the insulated case than for the reference case for which there is no insulation. One explanation that serves to support this result is based upon consideration of the controlling heat transfer medium. During a charging cycle the heat transfer between the air in the wellbore and the surrounding material is controlled by the heat conductance of the surrounding material. During reservoir closure the heat transfer is controlled by the low conductance of the air in the wellbore. Also, this cycling only represents the cycling of the air temperature in the wellbore. The heat capacity of the surrounding material is so large by comparison to the heat capacity of the air that the

Fig. 3. Effect of Wellbore Heat Transfer on Thermal Energy Recovery

Fig. 4. Thermal Cycling in the Reference Reservoir, Week 1

Fig. 5. Thermal Cycling for an Insulated Wellbore, Week 1

amplitude of the thermal cycling in the surrounding material decreases rapidly from the surface of the wellbore.

Preheating

In Fig. 3 the effects of preheating are shown by curves 2 and 5 which should be compared to curves 1 and 4, respectively. The effects of preheating on thermal energy recovery are seen to dissipate after only about 20 weeks. In addition to the initial improvement of thermal energy recovery, preheating reduces the amplitude of the initial thermal cycling although temperatures are generally higher. However, the effects of preheating dissipate rapidly so that after 1 year the thermal cycling of the preheated case is indistinguishable from the nonpreheated case.

RESERVOIR ANALYSIS

The reservoir analysis was intended to characterize the fluid and thermal response of the reservoir to conditions that were encountered in the porous zone by virtue of inclusion of the vertical dimension. The principal measure of the fluid response was the quasi-steady-state difference between the wellbore boundary pressure and the reservoir average pressure. This pressure difference represents the work required to overcome fluid friction in the porous zone. The thermal response that was of interest was the temperature distribution. In general, factors which perturb the flow field and the resultant quasi-steady-state pressure difference also affect the temperature distributions because the primary mode of energy transport is by convection.

Pressure Response

The parameters that were identified as important to the pressure response that required the inclusion of the vertical dimension to permit their evaluation were the producing length of the wellbore, and anisotropic and stratified permeability. The producing length of the wellbore proved to be the more important of these parameters. In Fig. 6 the quasi-steady-state pressure difference is plotted against the permeability ratio. The large effect of the producing length on the pressure loss suggests that the flow area at the wellbore-porous material interface is extremely important. At this interface the porous zone flow velocities are at their maximum values. The series of lines in Fig. 6 are drawn for various producing lengths in a 30.5-m-thick (100-ft-thick) reservoir. The producing lengths begin at the top of the porous zone.

The large effect of the producing length on the pressure loss suggests that the flow area at the wellbore-porous material interface is extremely important. At this interface the porous zone flow velocities are at their maximum values. These flow velocities dominate the reservoir pressure loss. The results dealing with producing length suggest the importance of extending the producing section of the wellbore through the entire reservoir thickness, to the extent possible, to avoid excessive flow losses.

The results shown in Fig. 6 suggest that the permeability ratio has a much smaller impact on pressure loss in the reservoir. For these cases the horizontal permeability was fixed at 500 md. Since flow from the wellbore is predominantly radial, for the case of the producing length being equal to the reservoir thickness, there is no noticeable effect of the reduced vertical permeability on the pressure response. For producing lengths less than reservoir

Fig. 6. Quasi-Steady-State Pressure Difference Versus the Permeability Ratio for Various Producing Lengths m (ft), Reservoir Thickness = 30.5 m (100 ft)

thickness, a portion of the air must expand vertically after entering the porous zone. As the air moves away from the wellbore, the vertical flow area increases dramatically so that vertical flow velocities are small. As a result, the contribution of the vertical flow to the pressure drop is small even for cases of significantly reduced vertical permeability and reduced producing lengths.

The effects of stratification of permeability were evaluated by modeling a 3.81-m-thick (12.5-ft-thick) layer of 100 md material, the top of which was 15.2 m (50 ft) from the top of the porous zone. The surrounding material was fixed at 500 md. A series of cases were evaluated whereby the producing length of the wellbore, beginning at the top of the porous zone, terminated above, within, and below the low permeability layer. The effect on the pressure response for these cases was similar in magnitude to the effect of the permeability ratio.

Thermal Response

Since the primary mode of energy transport in the porous zone is by forced convection, the thermal behavior of the porous zone will be largely determined by the mass transport. Factors affecting the mass transport that would affect the radial uniformity of the flow and that required the two-dimensional modeling for analysis included the producing length of the wellbore and stratified permeability. In addition, phenomena is present, even in homogeneous reservoirs, that adds to the maldistribution of thermal energy in the reservoir. These include natural circulation, heat losses to the vertical boundaries and non-uniform flow distribution from the wellbore. However, these additional effects are of less importance. A discussion of their analysis will be provided in the topical report to be issued by PNL.

An example of the effect of the flow disturbance on the thermal distribution is shown in Fig. 7 where vertical temperature profiles for various radii are shown for the reference reservoir and for a case in which the producing length is 7.62 m (25 ft). This flow disturbance concentrates the thermal energy at the top of the reservoir. The thermal energy concentration and the steep thermal gradients may present problems from the standpoint of the structural and geochemical stability of the reservoir. Figure 7 is composed of data taken during the first weekly cycle.

Even in the homogeneous reference reservoir vertical temperature gradients exist, as shown in Fig. 7. These result from non-uniform flow distributions caused by the header effect of the wellbore. These temperature gradients, once developed, stabilize quickly, apparently due to the balancing effect of other heat transfer mechanisms.

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

The results of the computer analysis have led to quantification and characterization of certain behavior of the underground CAES system that could only be addressed by a multi-

Fig. 7. Vertical Temperature Distributions at Various Radii (m (ft)) for Producing Lengths of 30.5 m (100 ft) (Solid Lines) and 7.62 m (25 ft) (Dashed Lines)

dimensional model. According to the results obtained by the numerical modeling, the following statements can be made regarding the effects of the vertical parameters of the reservoir. With regard to wellbore heat transfer:

- The recovery of thermal energy can be significantly reduced due to heat losses in the wellbore.
- Wellbore thermal insulation was shown to provide significant potential for improving thermal energy recovery.
- Heat losses from an uninsulated wellbore reduce the thermal cycling and lower the temperature in the porous zone.
- While wellbore insulation improves thermal energy recovery, the wellbore and porous zone are exposed to greater extremes of thermal cycling and higher temperatures.
- Preheating the reservoir may result in significantly improved thermal energy recovery and reduced thermal cycling during the initial weeks of reservoir operation.
- The effects of preheating are rapidly dissipated.

With regard to thermal behavior in the porous zone:

- The most important factor in determining the thermal distribution in the porous zone is the forced convection flow field.

With regard to the fluid behavior in the porous zone:

- The producing length should be maximized to avoid excessive pressure losses.
- Reduced vertical permeability does not significantly affect the overall pressure loss in the porous zone.
- Stratification of permeability has a greater effect on pressure loss in the reservoir when the producing section extends through the layer.

The results of this investigation lead to the next phase of model development. The importance of the producing length of the wellbore with regard to reservoir pressure loss was shown. For porous zones having a liquid phase water boundary below the air storage zone, the producing length will necessarily be less than the storage zone thickness. This will be required to prevent the production of water in the wellbore due to water coning. The degree of water coning will depend on such parameters as producing length, air mass flow rates, permeability/saturation relationships, storage zone thickness, and water zone thickness. Development of the model and the analysis of these and other subsequently identified parameters will constitute the next step of this research effort.

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