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**Simulation of Coupled Thermal-Hydraulic-Mechanical
Interactions in Fluid Injection into Fractured Rocks**

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Simulation of Coupled Thermal-Hydraulic-Mechanical Interactions in Fluid Injection into Fractured Rocks

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INTRODUCTION

The deformation of fractured rocks in response to fluid pressurization (e.g., by fluid injection) is a well-known phenomenon. Repressurization of hydraulically induced fractures in hydrofrac experiments is commonly used to obtain better estimates of in situ stresses. In this procedure the compressive stress in the fracture is neutralized by the pressure of the injected fluid, resulting in the complete separation of fracture surfaces. The deformation process, both in the rock as a whole and in the fracture specifically, is a coupled phenomenon. Thus far, the realistic simulation of fluid injection has not been possible because of the lack of data and the complexity of analysis. These limitations are even greater if one considers nonisothermal injection, which is used in hot-dry-rock experiments or cold-water flooding of oil reservoirs. Cold-water flooding entails a triply coupled process among the flow of heat, the flow of fluid, and the host medium deformability. Theoretical developments of Nowacki (1962) and other observations (e.g., Stephens and Voight, 1982) have pointed to the important role of thermal stress in the process of fracture deformation. Even though the scarcity of data and complexity of the processes prevent the realistic simulation of thermal-hydraulic-mechanical (THM) phenomena, the availability of numerical procedures (Noorishad et al., 1984) does allow a scoping analysis of some observations to be made. This article is intended to explain the observations made for the case of cold-water flooding of an oil reservoir.

THEORETICAL CONSIDERATIONS

Field equations of the THM phenomena, the general setup of a THM initial boundary value problem, and a numerical solution approach are given in Noorishad et al. (1984). That work also provides a basis for an understanding of the role of thermal stresses in the THM phenomena through inspection of the stress-strain relationships. In the formulations presented there, the *temperature* term is similar to the *pressure* term, with Biot's coupling coefficient (Biot, 1941) replaced by $E\gamma/(1-\nu)$, where E and ν are elastic moduli and γ is the linear thermal expansion coefficient. Solutions of uncoupled thermoelasticity, such as that of thermal stresses in an elastic thick-walled cylinder (Nowacki, 1962), provide a good insight. The variation in the tangential stresses at the inner cylinder boundary, caused by a change in temperature ΔT , is given as

$$\Delta\sigma_{\theta\theta} \text{ at } r=a = - \frac{\gamma E \Delta T}{1-\nu} \quad (1)$$

where a is the inner cylinder radius and tension is assumed positive. A change in temperature of about 10°C can create stress variations from 1 to 10 MPa, depending on the magnitude of the elastic moduli used in the calculation. It is obvious that such stresses could exceed the tensile strength of rocks in certain cases. To investigate the role of thermal stresses in circumstances where transport of energy is enhanced by fluid flow, as well as in conjunction with the mechanical aspect of the flow of fluids, numerical techniques such as the code ROCMAS (Noorishad et al., 1984) must be used.

APPLICATION

The numerical simulation in this work is based on semiquantitative data on cold-water flooding experiments provided by an oil company. In these experiments, it was noticed that hydrofracturing and/or reopening of existing fractures in the warm reservoir consistently took place at pressure gradients that were 1.5×10^{-3} MPa/m less than the expected values. For a reservoir at a depth of about 3000 m, the above reduction in gradient implies a shut-in pressure reduction of about 5 MPa. Equation (1) shows that this corresponds to a 10°C average cooling of the rocks near the well for a hard host rock. Using the code ROCMAS (Noorishad et al., 1984), we constructed a hypothetical two-dimensional (x - y) model of the reservoir to study this problem. Table 1 provides the data used in this model. Figure 1 shows a sketch of the geometry and the initial and boundary data. As can be seen, a fracture spans the geometry of the model. In the

Table 1 Data Used for Nonisothermal Fluid Injection into Fractured Rocks

Material	Property	Value
Rock	Mass density, ρ_s	$2.5 \times 10^3 \text{ kg/m}^3$
	Porosity, ϕ	2.0×10^{-1}
	Young's modulus, E_s	50.0 GPa
	Poisson's ratio, ν_s	0.25
	Solid thermal expansion coefficient, γ	$8.0 \times 10^{-6}/^\circ\text{C}$
	Specific heat, C_{ss}	$2.1 \times 10^{-1} \text{ kJ/kg}\cdot^\circ\text{C}$
	Thermal conductivity, K_M	7.65×10^{-4}
	Permeability, k	$2.5 \times 10^{-13} \text{ m}^2$
	Biot's storativity constant, $1/M$	5.0 GPa
	Biot's coupling coefficient, α	1.0
Fracture	Initial aperture, $2b$	10^{-7} m
	Biot's storativity constant, $1/M$	1.0 GPa
	Initial normal stiffness, k_n	100 GPa
	Initial stiffness, k_s	10 GPa
	Friction angle, ψ	30°
	Cohesion, C	0.0
	Porosity, ϕ	1.0

field experiments, the wells are pumped at constant rates until well pressure stabilizes; the rate is then increased by a constant amount, and the procedure continues for a period of a day or more, during which one or two hydrofracturing episodes are observed. A realistic simulation of the experiment is not possible; instead, we seek a crude approximation. We do this by obtaining a THM response of the model through a series of steady-state hydromechanical (HM) calculations that use the results of a coupled transient thermal analysis. The approximation is justified because of the large difference between the time constants for fluid flow and heat flow. The fracture in the model is regarded to be closed initially (with aperture 10^{-7} m). Pressurization of the reservoir opens the fracture

Figure 1. Schematic geometry of the model and initial and boundary data.

elastically against the sustained compressive stresses. This increase in the aperture allows further penetration of the pressure front until the fracture goes into a tension state and hydrofracturing takes place. In the simulations, the occurrence of hydrofracturing is marked by instability of the system in the solution. The presence of thermal stresses accelerates this phenomenon. Figure 2 shows the results of an isothermal (HM) calculation and a nonisothermal (THM) calculation of the model. As can be observed in the figure, the system becomes unstable at an injection pressure close to 10 MPa less than that of isothermal injection calculations. Figure 3 depicts the advancement of the thermal front in the fracture, and Figure 4 displays the calculated thermal-hydraulic and THM pressure distributions in the fracture as the fracture walls separate from each other with the advancement of time.

CONCLUSION

We have constructed a THM model of a cold-water flooding experiment in an oil reservoir. Preliminary calculations with this model show that hydrofracturing occurs earlier when thermal effects are taken into account than when they are ignored.

Figure 2. Variation of fracture aperture in response to pressurization.

Figure 3. Advancement of the thermal front in the fracture.

Figure 4. Pressure profile in the fracture for isothermal and nonisothermal injection episodes.

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