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GLOBAL vs. LOCAL DIFFUSION PHENOMENA IN UNDERGROUND HEAT AND MASS TRANSFER

by

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ABSTRACT

Classical descriptions of fluid flow in porous media have always assumed that the storage and fluid flux are dependent only on the local pressure and its gradient, and thus that local mass conservation involves only the pressure at nearest nodal points. This leads to conveniently banded matrices for resulting simulators employed by groundwater hydrologists and petroleum engineers alike. Some non-local dependency has been recognized, with the advent of the Biot consolidation theory, in which pore-pressures are induced by stresses which are governed by elliptic rather than parabolic equations. However, an even more dramatic non-local effect involves the presence of fractures: although these are often lumped into dual-porosity and other such simple models, they do in fact change the nature of both the flow and the stress transmission problem. While some basic diffusive features can still be derived, the detailed simulation problem is considerably harder and introduces many new complexities to the numerical modelling process. Sample problems and their solutions give particular application to the important process of underground fracturing, on which the authors have conducted extensive theoretical and laboratory studies, with a broad range of applications to practical field problems. One conclusion is that the currently popular use of large-scale complex flow simulators often serves more to mislead than enlighten the scientific/engineering community, when these simulators do not incorporate the primary global mechanisms of heat and mass transfer.

Introduction

The physics and mathematics of fluid flow in porous media have been the object of intense scrutiny over the past half century at least. These studies have emerged from many different disciplines of physics and engineering: early work was motivated by the need to understand water-wells (e.g. Muskat, 1937) and later to make simple calculations of oil and gas production from underground strata (e.g. Muskat, 1937, Allen & Roberts, 1978): increasing complexity was added as consideration was given to fluid infiltration through dry soils (e.g. Parlange, 1971-72), phreatic surfaces in earth-dam applications (e.g. Muskat, 1937) and water/gas-driven mechanisms in petroleum reservoirs (e.g. Allen & Roberts, 1978). Gradually, the more complex question of multiple phases residing in shared pore-space was addressed, both in theoretical tomes and in practical applications (e.g. Bear, 1972, Aziz & Settari, 1979), resulting in key concepts of relative permeability and interface instabilities. Because of the many different practical sources of these studies, the physical units employed (e.g. for permeability) vary greatly, but the fundamental mathematical methods are the same, and the associated numerical methods have been developed to a high level of complexity (e.g. Hitchon et al., 1984-88, SPE Symposia of Reservoir Simulation).

However, as in many other areas of engineering science, such as structural analysis, the momentum of rapid advances in analytical and numerical methods has carried some of the modelling capabilities well beyond the domain of their practical usefulness. This is especially true because a number of fundamental mechanisms are often ignored in arriving at some computational solution. As a result, although such solutions are often quoted to many decimal places, they may not even be correct in the first significant figure. This point was emphasized by the author ten years ago (Cleary, 1978) in the context of structural analysis.

The purpose of this paper is to identify similar unresolved problems or neglected analyses in the context of underground fluid migration, whether for hydrogeological, petroleum production, waste disposal or other applications.

To crystallize the issues, the paper will discuss three particular mechanisms which may cause dramatic departures of reality from the typical smooth continuous descriptions on which mathematical analysis and reservoir simulation have concentrated over the many years of development cited above. The three mechanisms are the following:

1. Poroelastic behavior of some or all of the medium in question.
2. Fluid interface instabilities in response to the disturbance.
3. Large-scale evolution of solid geometry, such as opening or closing of fracture networks, hence change of conductivity.

The common essence of these mechanisms is that they generate a global, rather than a local character in the problem under scrutiny. One major result is that there can be a dramatic effect of size or scale. Dimensions of the disturbance responsible for the variation of field quantities may appear strongly because of Mechanism 1; the swept region may be altered quite dramatically by Mechanism 2; and the sweep time may be greatly reduced or increased by Mechanism 3. One or more of these mechanisms may be found to have strong influence in a wide variety of applications, so that they merit primary consideration in scientific analysis and engineering design, as we now proceed to illustrate.

Poroelastic Effects in Porous Media

The earliest engineering motivation for understanding the coupling of fluid pressure and solid stress apparently arose from the observation of consolidation under structural foundations (e.g. Biot

& Clingan, 1942). This theory was evolved gradually by Biot and analyses were performed by numerous researchers for various civil engineering problems (e.g. McNamee & Gibson, 1960, Booker & Small, 1975). The broader implications of the theory were recognized and developed by Rice and Cleary (1976), which led to the derivation of some fundamental solutions by Cleary (1977). The basic governing field equations were derived in various forms but may be effectively represented here in terms of stress components σ_{ij}, displacements u_k and pore-pressure p as follows (e.g. Cleary, 1977):

$$\sigma_{ij,j} = \left[L_{ijkl}u_{k,l} + B_{ij}p\right]_{,j} = -F_i \qquad \text{(1a)}$$

$$\left[\bar{B}_{kl}\sigma_{kl} + cp\right]_{,kk} = \partial p/\partial t - S \qquad \text{(1b)}$$

in which L_{ijkl}, B_{ij}, $\bar{B}_{kl}$ are poro-elastic moduli and c is the diffusivity of fluid flow (see Eqn. 1g); F_i and S are the body-forces and fluid source distribution functions, respectively.

These equations illustrate two basic points:

- The displacements (or stress) and pore-pressure are coupled; changes in one affect the other, so all of them evolve in time.
- The governing equations have different field characteristics; the displacement equation is elliptical while the pore-pressure equation is parabolic: without the coupling, each would have a distinctly different variation in space and time.

The consequence is that disturbances in pore-pressure are transmitted instantaneously to distances of order the disturbance size, in contrast to the slower diffusive transmission implied by Eqn. 1b. However, the latter diffusion does then take place and the displacement in Eqn. 1a evolves, from the "undrained" to the "drained" response.

To illustrate this phenomenon, we cite the pore-pressure at distance $x > l$ on the plane of a fracture with constant opening Δ between $x = -l$ and $x = +l$:

$$p = \frac{GB(1+v_u)}{3\pi(1-v_u)}\left\{\frac{e^{-\frac{(x+l)^2}{4ct}}}{x+l} - \frac{e^{-\frac{(x-l)^2}{4ct}}}{x-l} - \frac{2l}{(x+l)(x-l)}\right\}\Delta \qquad \text{(1c)}$$

in which the induced pore-pressure ("Skempton") coefficient B is

$$B = (1 - K/K_s)/\left[1 - K/K_s + \phi K/K_f - \phi K/K_s\right] \qquad \text{(1d)}$$

and the "undrained" Poisson ratio is

$$v_u = (3v + \bar{B})/(3 - \bar{B}), \bar{B} \equiv B(1-2v)(1-K/K_s) \qquad \text{(1e)}$$

These expressions involve porosity ϕ, the "drained" Poisson's ratio v and the drained matrix bulk modulus K (called K_s and K_f for solid and fluid components, respectively); the shear modulus G is related to K these by the isotropic elastic identity

$$G = 3K(1-2v)/2(1+v) \qquad \text{(1f)}$$

We note that the pore-pressure evolution in time is still controlled by the diffusivity c which can be related to fundamental poro-elastic parameters by

$$c = \frac{k}{\mu}\left[\frac{2GB^2(1-v)(1+v_u)^2}{9(1-v_u)(v_u-v)}\right] \rightarrow \frac{kK_f}{\mu\phi} \text{ as } v_u \rightarrow v \qquad \text{(1g)}$$

which involves the permeability k and the fluid viscosity. μThis reduces to the classical diffusivity of a rigid porous medium as constituents become incompressible ($v_u \rightarrow v$, $B \rightarrow 0$); however, when $B > 0$, we find an instantaneous pore-pressure response ($p = -B\sigma_{kk}/3$) at $t = 0$ (Rice & Cleary, 1976; Cleary, 1977), which is not present in the classical theory of rigid porous media. The most appealing application of this pore-pressure response is the potential to use it as a fracture diagnostic by pressure measurement in adjacent wells with downhole packers and pressure gauges, using a generalization (integrations) of eqn. (1c) for realistic 3-D fracutre geometries.

Interface Instabilities in Porous Media

Taylor-type instabilities have been well known in the fluid mechanics literature for many decades, based on experiments in Hele-Shaw apparatus (Figure 1a) and other observable experimental configurations (Figure 1b). As well, the importance of these phenomena in underground fluid migration have long been recognized and alluded to in the petroleum literature (e.g. Allen & Roberts, 1978): effects such as "watering out" of wells are attributed to such effects as greater water mobility and gravitational coning of oil/water interfaces.

However, the numerical schemes employed to model such problems are often incapable of capturing the phenomenon with acceptable levels of accuracy. The key involves the choice of mesh and interpolation functions and especially the ability to track a perturbation as it develops from an initially smooth interface. An illustration of the very complex patterns, resulting from evolution of such instabilities in porous media, is provided in Figure 1b.

A comprehensive discussion of the subject is beyond our scope here, but a detailed review may be found in Barr & Cleary, 1984.

In addition, a recent Ph.D. thesis by Fonseca (1992) has focused on the issue of "encapsulation", which allows higher viscosity fluids to migrate more rapidly with the aid of a low-viscosity envelope, especially in the kinds of fracture growth environments discussed in the next section.

Evolution of Fracture Geometries

The most complex, yet most important, mechanism for large-scale transport of underground fluid is that of progressive opening (and/or closing) of one or more fractures. Such a mechanism has profound implications for a great variety of practical applications in such areas as geophysics, petroleum engineering and hydrology (e.g. Cleary, 1981-88):

- Ability to inject fluids (through wellbores) into underground formations; examples include waterflooding, tertiary oil recovery with polymers and steam flooding of heavy oil reservoirs (e.g. see sample applications in Proceedings of the Society of Petroleum Engineers).
- Ability to withdraw fluids from underground formations; examples include naturally-fractured reservoirs and low-permeability (gas) reservoirs, for which the creation of (propped) open hydraulic fractures is essential (e.g. Cleary, 1988). Indeed, the natural fractures in most reservoirs were probably often induced by high pressure and hydraulic effects.
- Ability of hydrocarbons to migrate from source rocks to reservoirs; migration through "impermeable" strata in a reasonable time is made possible by induced fracturing, driven by tectonic (faulting), thermal and/or hydraulic mechanisms.
- Ability to extract heat from underground thermal reservoirs: both "wet" geothermal and hot dry rock (HDR) involve some fracturing, but the HDR resource is much greater and is more dependent on thermal fracturing for its success (e.g. Barr & Cleary, 1980, Armstead & Tester, 1987).

We have conducted studies on these and other applications over the past ten years. A detailed review of our work is impossible here, but references may be found in our annual research reports (Cleary, 1981-87). A sampling of that work is provided here to illustrate the theme of the paper.

We should emphasize that the fractures under discussion here are those induced by the stress, pressure and temperature condition associated with the process: thus, they involve a complete and complex (non-linear) coupling between the fluid flow, heat transfer, stress alteration and the geometry of fractures allowing these changes to occur. This contrasts strongly with more conventional studies of pre-existing ("natural") fractures, where some a priore geometric distribution is assumed, or simple variations thereof are adopted - for instance, allowing local permeability to change, depending on local pressure and stress only: such models will always fail to capture the essence of the mechanisms described in subsequent sections, and will lead to serious errors in engineering designs aimed at production or (waste-related) retardation of underground fluid flow.

(a) Single Hydraulic Fractures vs. Diffusive Fluid Penetration

Simple ("Perkins-Kern") Fracture Geometry

The simplest illustration of the role that fractures play in fluid transport may be achieved by calculating the extent L_D of fluid penetration under pressure p_f into an unfractured medium with permeability k, porosity ϕ, pore-pressure p_T and pore-fluid viscosity μ, which may be represented as follows:

$$L_D = \bar{\gamma}_D \sqrt{k}\, \sqrt{t/\tau_D} \quad \text{(2a)}$$

in which the diffusive characteristic time τ_D takes the form

$$\tau_D = \mu\phi / (p_f - p_T) \quad \text{(2b)}$$

for an "initially dry" medium, as against a similar form

$$\tau_D = \mu\phi / \bar{K} \quad \text{(2c)}$$

for an "initially saturated" medium with effective bulk modulus $\bar{K}$ Cleary, 1976). The proportionality constant $\bar{\gamma}_D$ is of order unity.

This may be contrasted with the penetration L_F achieved by an hydraulic fracture of fixed height H (e.g. Cleary et al., 1988, 1991, Figure 2a), namely

$$L_F = \bar{\gamma}_F H \sqrt{t/\tau_F} \quad \text{(2d)}$$

$$\tau_F = (\mu/\bar{E})\left[\bar{E}/(p_f - \sigma_c)\right]^3, \; \bar{E} = E/4(1 - \nu^2) \quad \text{(2e)}$$

in which σ_c is the earth stress acting normal to the fracture being created and $\bar{E}$ is the effective "crack-opening" modulus of the medium, derived from Young's Modulus E and Poisson's ratio ν. The proportionality contrast $\bar{\gamma}_F$ is of order 0.0.1.

The ratio of penetrations may now be calculated as

$$L_F^2 / L_D^2 = \left(\frac{\bar{\gamma}_F}{\bar{\gamma}_D}\right)^2 (H^2/k)\,(p_f - \sigma_c)^3 / \bar{E}^2 \left[\bar{K}, (p_f - p_T)\right] \quad \text{(2f)}$$

This clearly illustrates the global dimension H associated with fracture propagation, as against the local permeabillity characteristic k associated with diffusion.

It is interesting to calculate some representative estimates for L_F/L_D by inserting some typical values for the parameters:

$$k = 1\text{mD} = 10^{-15}\text{m}^2;\; H \simeq 30\text{m};$$
$$\phi \simeq 0.1;\; \bar{\gamma}_F/\bar{\gamma}_D \simeq 0.1 \quad \text{(2g)}$$
$$\bar{K} \simeq \bar{E} \simeq 10^4\text{MPa};\; p_f - \sigma_c \simeq 10\text{MPa} \simeq p_f - p_t;$$

The results may be phrased as alternatives

$$L_F^2 / L_D^2 \simeq 10^4 \left[10^3, 1\right] \quad \text{(2h)}$$

for the respective cases of initially (dry, saturated) media: the fractures grow three to four orders of magnitude faster than the fluid diffusion can occur.

Illustrative Cross-Sectional Model of Fracture Growth

Actually, of course, Eqn. 2d is a very special case of the general solution for fracture propagation, used here just to make easy comparison with Eqn. 2a. In general, the fracture height does not stay constant, but rathers grows like

$$dR/dt = \bar{\gamma}_F R/\tau_F,\; H = R(\Theta = \pm\pi/2) \quad \text{(3a)}$$

in which $\bar{\gamma}_F$ depends on the reservoir conditions, such as variation of σ_C, k, and $\bar{E}$ which dictate the growth at each instant of time. If we regard R as any generic dimension of the fracture, then the purpose of our full 3-D simulations (e.g. Cleary, 1988, Cleary et al., 1988), is to evaluate $R(\Theta, t)$ for all possible variations of fracture geometry (e.g. Figure 2a) and reservoir conditions: Eqn. 3a simply focuses the discussion by displaying the general character of growth-rates. Note that the reference point is chosen at the center of the wellbore cross-section, just for illustration; the fracture will grow asymmetrically in general.

The source of the result in Eqn. 3a may be illustrated, along with the non-local character of the process, by writing the overall governing equations for such a representative cross-section of the 3-D fracture (e.g. Figure 2b). The 3-D formulation and implementation is given by Cleary (1980) and Cleary et al. (1988). The primary equations are those of local mass conservation and fluid flow at any point s along the cross-section:

$$\frac{\partial q}{\partial s} + \frac{\partial \delta}{\partial t} = -q_L\,;\quad q = -\frac{\delta^3}{12\mu}\frac{\partial p}{\partial s} \quad \text{(3b)}$$

which requires additional equations for the fluid flux q, crack opening δ and leak-off to the reservoir q_L in order to obtain a solution like Eqn. 3a. The greatest source of complexity in obtaining this solution is the fact that crack-opening $\delta(s, t)$ at any point depends at least on the pressure at all other points on the fracture surface $p_f(s, t)$; this global dependence may be expressed most generally by means of an integral equation

$$\delta(s, t) = \int_{S_{c}} ds' \gamma(s, s', t) \left[p_f(s', t) - \sigma_c\right]. \quad \text{(3c)}$$

This involves an influence function $\gamma(s, s', t)$, which depends on the fracture geometry $S_c(t)$ at time t and can be obtained only for very special geometries; although a number of modellers have employed this approach, because it greatly simplifies their work, it does limit them to very simple geometries (e.g. homogeneous infinite regions and circular or Perkins-Kern geometries). To overcome this limitation, we actually use an inverse relationship of $p_f - \sigma_c$ in terms of an integral over the crack-surface $S_c(t)$ of $\delta(s)$ with an influence function $\gamma(s, s')$ which can be determined for a wide variety of geometries. We call this the surface integral equation (SIE) approach and we have hybridized it with a finite-element approach (e.g. Keat et al., 1988) to get the most powerful existing approach (SIFEH) for solution of fracture problems.

Models for Field Applications

Practical field applications (e.g. Cleary, 1988, Figure 2) most often involve specified flow rate $Q(t)$, rather than specified pressure $p(t)$. Conversion between them requires use of the flow law, which may be expressed as follows:

$$(Q/2\pi R_e)^m = -\Delta^{2n+1}(\partial p/\partial r)/\bar{\mu} \quad \text{(3d)}$$

in which $2\pi R_e$ is the effective injection perimeter [= $4H$ for Eqns. 2a-e]. In fact, Eqns. 3a and 2d are derived by combining Eqn. 3b (with $n = m = 1$) with an equation for crack-opening Δ, namely

$$\Delta = \gamma_0 (p_f - \sigma_c) R/\bar{E}\ , \quad \text{(3e)}$$

then representing the pressure-gradient with a flow coefficient γ_F:

$$\delta p/\delta r = \gamma_F (p_f - \sigma_c)/R \quad \text{(3f)}$$

Finally, the overall fracture volume must be related to injected volume (Figure 2b):

$$\int_0^t Q dt = \gamma_V LH\Delta + \int_0^t dt \int_{A(t)} q_L dA \quad \text{(3g)}$$

in which q_L is the rate of fluid leak-off from the fracture to the pore-space, as described by Eqn. 2a for instance.

The various coefficients appearing above γ_0, γ_F and γ_V are determined by use of full 3-D simulators (Cleary et al., 1988), checked against laboratory experiments (e.g. Johnson and Cleary, 1991; Cleary, 1988) and then implemented in lumped models of the kind described by Eqns. 4a-e. These models have been employed in a wide variety of field operations (e.g. Cleary, 1988, Cleary et al., 1991) to determine the reservoir properties k, σ_C, $\bar{E}$ and their variations; this determination is done by matching observed pressures with those calculated by the models described above, e.g. as provided by Cleary et al., 1991 (and their references). The process very much resembles the history-matching often conducted by hydrogeologists and petroleum engineers to establish reservoir properties, such as permeability, and geometric features such as boundaries and natural or induced fractures. However, the process does require real-time analysis, on a much shorter time-scale than reservoir production, in order to be effective in improving hydraulic fracture treatments before they are finished pumping. The field-oriented technology which has been developed in this context (e.g. Cleary, 1991, Cleary et al., 1988, Figure 2a) is now being widely used by the petroleum industry, to greatly alter the level of understanding and application of underground fracturing operations.

(b) Multiple Self-Driven Thermal Cracks vs. Thermal Diffusion

An even more dramatic illustration of the role which fluid flow in cracks can play in accelerating the process of reservoir access is that identified by Barr and Cleary (1980), in the context of heat extraction from Hot Dry Rock (HDR). An active field project of the Los Alamos National Laboratory at Fenton Hill, New Mexico, was the major motivation for the study: two wellbores were drilled into near-surface hot granite and, after much effort, they were connected by a fracture to allow fluid circulation and to serve as a heat-exchanger (e.g. Armstead & Tester, 1987, Figure 3a).

The key issue involved is, of course, the potential rate of heat extraction from the reservoir: an economically viable project requires that the capital cost of each wellbore-fracture installation (in addition to surface equipment such as turbine/electric generator sets) be returned in a reasonable time, with an adequate rate of return on the investment. We quickly realized that the heat flux associated with thermal diffusion would be constrained by the rate of penetration of the cooling front from the fracture walls, namely

$$V_H = \bar{\gamma}_H \sqrt{C_H/4t}\ ,\ L_H = \bar{\gamma}_H \sqrt{C_H t} \quad \text{(5a)}$$

in which C_H is the thermal diffusivity (i.e. conductivity/specific heat): typical values of C_H for dry rock materials are 10^{-6} m^2/sec, which implies a penetration of the diffusive front, $L_H \sim 6\text{m}\sqrt{\#\ \text{years}}$ hence a time of 10,000 years for a penetration of 600 m. Unless drilling and fracturing costs are reduced dramatically, or the net asset value per unit area of reservoir is unrealistically great, the process of heat diffusion from the rock to the circulating fluid in a single fracture is far from the potential for an economical project.

However, if we consider the potential for secondary fractures (with spacing s and speed V_F) normal to the primary fracture (Figures 3a,b), a dramatic new mechanism of heat extraction becomes possible. Fluid may circulate in the secondary cracks also and cool their surfaces, thus generating an additional driving mechanism: as their surfaces cool, these cracks are propagated further by the resulting contraction-induced stresses; as they propagate, they allow fluid to circulate through them, deeper into the rock mass, thus cooling and driving them further in a self-perpetuating fashion. This buoyantly-driven fluid circulation in the secondary cracks is a key factor in the process: otherwise, the cracks will not grow much further than the depth of penetration of the diffusive front (Eqn. 5a) and, therefore, they will not assist substantially in heat extraction.

Thus, the many previous studies of thermal cracking (see references in Barr & Cleary, 1980, Armstead & Tester, 1987), which had preceded our study of the self-driving mechanism, did not offer any potential for enhanced heat extraction: not alone is their speed of propagation limited to the pure conduction velocity in Eqn. 5a, but their spacing continuously increases roughly proportionally with depth of penetration, so that secondary fluid circulation would not greatly increase the rate of heat extraction.

Our analysis, including the self-driving mechanism, produced two major inclusions:

- The fracture spacing reaches a stable constant value s, which allows circulating fluid to extract heat at an almost steady rate
- The growth of secondary cracks reaches a steady speed V_F,

$$V_F = 0.8 C_H E_1^2 \Big/ \left[K_{IC} + (\sigma_C - P_f)\sqrt{s/2}\,\right]^2 \quad \text{(5b)}$$

in which K_{IC} is the fracture toughness of the rock and $E_1 = E\alpha(\Theta_0 - \Theta_F)/(1-\nu)$, using α for thermal expansion coefficient and $(\Theta_0 - \Theta_F)$ for the change of temperature from Θ_0, to Θ_F.

The consequences of Eqn. 5b are profound: even when the project is operated at pressures p_f below the earth-stress σ_c the thermal contraction $\alpha(\Theta_0 - \Theta_F)$ induces enough tensile stress to overcome the closure effects of $\sigma_c - p$ and fracture toughness K_{IC}; in addition, the cooling by fluid circulation in the cracks sets up a steady-state velocity V_F, which does not decrease dramatically with ongoing time like V_H in Eqn. 5a. Typical values for this velocity have been worked out for representative parameter values:

$$E = 4\times10^4\text{MPa};\ \nu = 0.3;\ K_{IC} = 2.5\text{MPa}-\sqrt{\text{m}}\ ; \quad \text{(5c)}$$
$$C_H = 10^{-6}\text{m}^2/\text{sec};\ \alpha = 8\times10^{-6}/{}^\circ\text{C};\ \Theta_0 - \Theta_F = 135^\circ\text{C}$$

For various values of operating pressures, p_f, we get various speeds and spacings: the actual allowable speeds are dictated by the requirement of (buoyancy-induced) convective flows through the fractures and our calculations (Barr & Cleary, 1980) are illustrated by Figure 3c, showing speed V_F vs. pressure-gradient available to drive the convective flow. For example, if the pressure gradient is of order 1 kPa/m, we get speeds of order 100 m/year. Although the detailed 3-D simulation of this complex problem has not yet been conducted, and field verification (e.g. Armstead & Tester, 1987) is still awaited, we postulate that:

- Heat may be extracted from HDR reservoirs in times of order decades, provided the convective self-driven crack mechanism, leading to Eqn. 5b, is operative. This contrasts with required times of order millenia when only conduction (Eqn. 5a) operates to extract heat from impermeable rock.

- The process can be operated at pressures below the closure stress, unlike the hydraulically-driven crack propagation described in Section (a). In fact, hydraulic fracturing with $p_f > \sigma_c$ would be too rapid to allow the convective heat transfer by fluid flow through the secondary cracks, which is essential to allow (conduction) cooling between these cracks.

(c) Pore-Pressure-Induced-Cracking (PPIC)

Another mechanism which has major potential to enhance fluid migration through fracturing is the induction of pore-pressure which is near or above the closure stress. These pressures can be released if they become higher, either than the effective stress keeping the cracks closed or than the current fluid pressure within the cracks; this can happen for a variety of reasons:

(i) The pore-pressures are actually higher than the least earth-stress component. This can happen when (lateral) earth-stresses are altered by tectonic action and/or the pore-pressures are elevated by thermal or tectonic effects. The best example of the latter may be the gradual cooking of organically-rich sediments during burial while the former may be due to stress release by erosion, thrust faulting, buckling, etc.

(ii) The primary fracture mechanism is thermal contraction, as in Section (b). The pore-pressure then acts as an assistance to the process, basically contributing to the fluid pressure p_f appearing in Eqn. 5b, which is below σ_c.

(iii) The pressures in much of the fracture may be above p but there may be critical regions, e.g. near the fracture perimeter, where the pressure is lower and the rate of propagation may be greatly accelerated by the leakage of pore-fluid into those regions. Cleary (1979) provides a detailed discussion of this process.

Since the first, condition (i), may be active in a variety of applications, from hydrocarbon migration and naturally-fractured reservoirs to fragmentation of brittle materials, we have conducted an experimental and theoretical study of the PPIC process. The details are provided by Vogeler et al. (1985), but the basic concepts and results may be described briefly here.

The process illustrated in Figure 4a was modelled by a distribution of cracks propagating simultaneously in a region which we regard as infinite on the scale of any individual crack. We modelled one generic crack driven by the flux of fluid from the pore-space into the opening crack space; a typical result is shown in Figure 4b, using non-dimensional variables defined by Vogeler et al. (1985).

To check the analysis, we performed a set of laboratory tests with unjacketed specimens in a pressure-vessel (Figure 4a, Vogeler et al., 1985). To generate the pore-pressure, we built up and held the pressure in the vessel until the specimens were saturated; then we rapidly dropped the pressure in the vessel, leaving a higher pore-pressure p than the confining stress σ_c. The expected result was the creation of multiple cracks of the kind modelled in Figure 4b. We might have anticipated that these cracks would be generated at excess pressures $p - \sigma_c$ above the "tensile" strength σ_T of the material. We quickly discovered something that we and others have guessed for many years: the small-scale σ_T is much greater than that measured by "large-scale" tensile tests; the required $p_f - \sigma_c$ was more than an order of magnitude greater than the strength measured in "Brazilian" strength tests. However, we did use these Brazilian tests to check the theory, as shown in Figure 4c: since strength is really determined by fracture toughness K_{IC} and crack size R, e.g. $\sigma_T \simeq K_{IC}/\sqrt{\pi R}$, we are able to determine $R(t)$ and compare very favorably with calculations in Figure 4b, or vice-versa, as shown in Figure 4c.

The implication is that the PPIC phenomenon produces fractures which are analytically predictable: they depend on the pressures and stresses in the region; on the fluid transport and mechanical properties of the rock material; and on the geometry of the region -- such as stratification and boundaries. This may be the basis of an analytical capability to handle realistic underground structures involved in hydrocarbon migration from source rock and in natural fracturing of overpressured reservoir rock structures.

Conclusions

We have reviewed a number of mechanisms which can cause dramatic departures of the actual behavior in underground transport processes from that predicted by conventional analytical or numerical techniques. Such mechanisms have not previously been included in scientific or engineering analysis, because they involve a number of very complex solid-fluid-thermal coupling effects and/or variation of geometry in the region being analyzed. We have first had to develop the computational tools to analyze these problems, then carefully study the physics of each mechanism and finally devise methodologies to test the models in laboratory and field environments. Our results are dramatically different from previous analyses with simplified models of pre-existing or uncoupled thermal and hydraulic fracturing, and we believe that they are essential for proper analysis.

The results of our efforts have been very rewarding, in opening up new insights into the many diverse applications in which these mechanisms are operating. Our studies (e.g. Cleary et al., 1981-91) have covered such applications as: artificial generation of one or more underground fractures from one or more wellbores (e.g. Narendran & Cleary, 1983, Papadopoulos et al., 1983), including the presence of various disturbances from fluid and heat injection and/or reservoir fluid production; the generation of natural fractures in over-pressured tectonically active and/or thermally varying reservoir conditions; the potential for migration of hydrocarbons across great distances and through initially impermeable strata: the underground instabilities which arise in large-scale multiple fluid flow processes; and the fragmentation of brittle materials with fluid pressure.

Many other applications remain to be studied, as human interaction with the underground evolves. These should include more detailed analyses of coupled thermal, hydraulic and solid deformation processes (e.g. Cleary et al., 1983, Chin & Cleary, 1987). Perhaps the most worrisome consequence of our studies, for modern-day activities, is its implication for the desired capability to isolate underground waste disposal sites, especially those for nuclear and chemical waste. There have not been any worthwhile studies of how the coupling, between waste migration and the potential thermal-hydraulic cracking associated with it, can affect the issue of waste containment; studies like those outlined in Eqns. 3-5 strongly indicate that such studies must be conducted before any confidence can be had in techniques currently being proposed for waste isolation.

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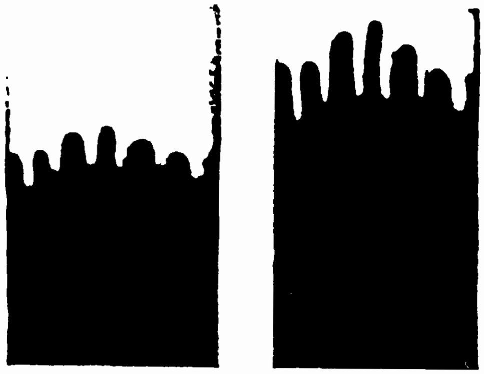
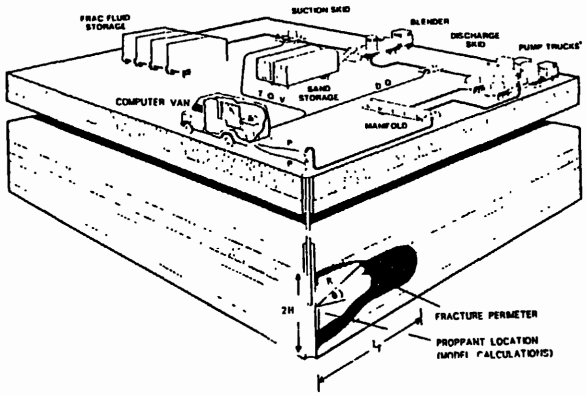
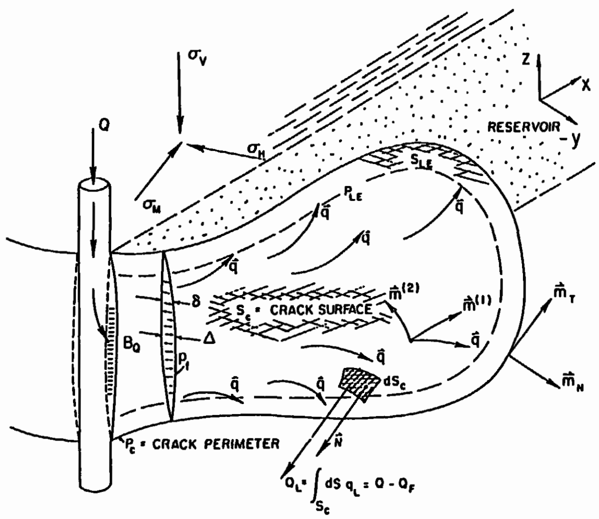


1a. Illustration of interface instability in Hele-Shaw apparatus; aqeous glycerine (black) displaces oil (white).

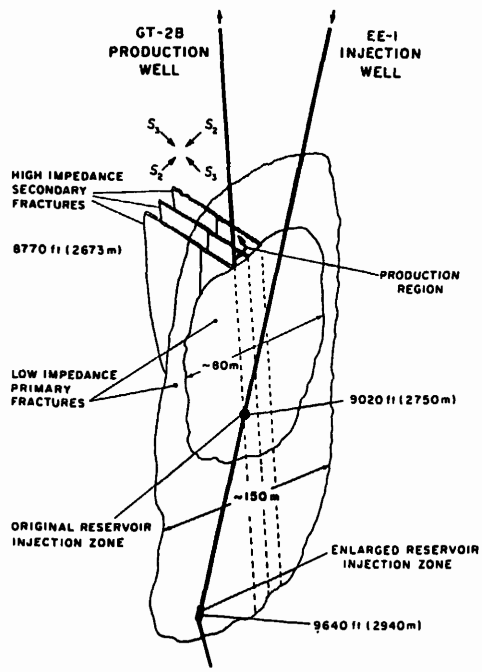
1b. Water (white) displaces oil (black) in a porous medium with 0.15 pore volumes of connate water.



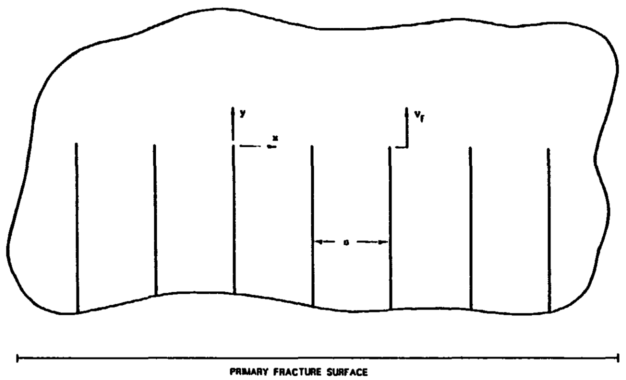
2a. Schematic of overall hydraulic fracturing operation, showing surface equipment and resulting underground fracture.



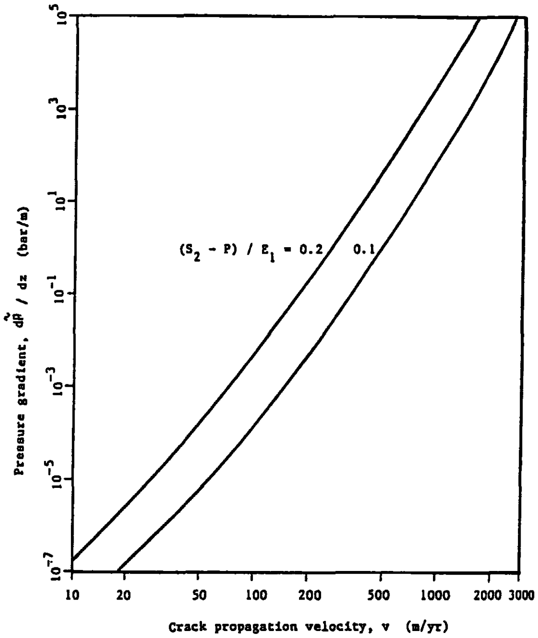
2b. Schematic of modelling variables employed in full 3-D simulation of hydraulic fracturing.



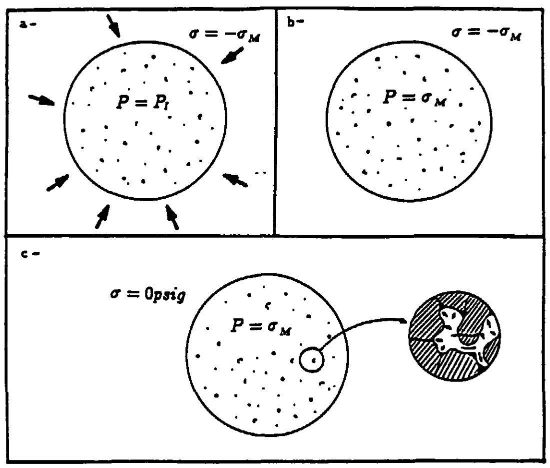
3a. Schematic of estimated wellbore and fracture configuration for created heat extraction from hot dry rock at Los Alamos Fenton Hill Site (Armstead & Tester, 1987).



3b. Simplified model of secondary fractures as infinite array of parallel, semi- infinite cracks with spacing s and propagation V_F (Barr & Cleary, 1980). This assumption of a stable array was verified by stability analysis.



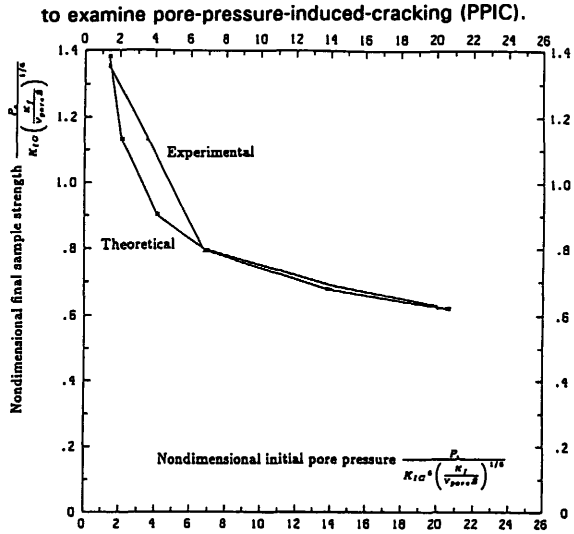
3c. Sample calculations of secondary crack growth speeds V_F illustrating the dominant dependence on the pressure-gradient driving convective fluid flow (Barr & Cleary, 1980).



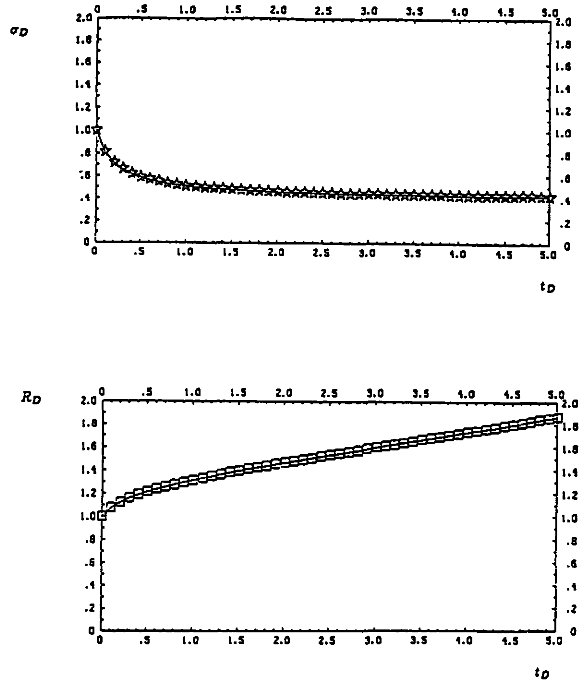
a- Before permeation $\sigma_{eff} = P_f - \sigma_c$ b- At saturation $\sigma_{eff} = 0$

c- Immediately after confining pressure release $\sigma_{eff} = \sigma_M$

4a. Illustration of laboratory process (Vogeler et al., 1985), used to examine pore-pressure-induced-cracking (PPIC).



4c. Comparison of model predictions vs. measured strength of samples in Brazilian tests after being subjected to PPIC process in Figure 4a (taken from Vogeler et al., 1985).



4b. Illustration of calculations for dimensionless crack growth vs. dimensionless time, R_D vs. t_D under PPIC conditions. The associated excess pressure is $(p_F - \sigma_c)/\sigma_c = \sigma_D$. [Dimensionless quantities are defined by Vogeler et al., 1985.]