Multiphase Flow in Fractured Rocks—Some Lessons Learned from Mathematical Models

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1. INTRODUCTION

Fractured rock formations encompass an enormous variety of hydrogeologic properties [*Bear et al.*, 1993; *National Research Council*, 1996]. For the recovery of resources such as oil, gas, and geothermal energy from fractured reservoirs, we are primarily interested in systems with well-connected fracture networks of high permeability and with good matrix permeability and porosity. For the purposes of underground waste disposal, we generally prefer media with the opposite characteristics, i.e., sparse and poorly connected fractures and low matrix permeability. Multiphase flow processes of interest in fractured media include two-phase flows of water-gas, water-NAPL (nonaqueous phase liquid), and water-steam, and three-phase flows of oil, water, and gas. Water seepage through the vadose zone is a special kind of multiphase flow process that is an essential component of the hydrologic cycle. It may often be described in approximate fashion by considering the gas phase as a passive bystander. Multiphase flows may be complicated by strongly coupled heat transfer effects, as in geothermal production and injection operations, in the thermally enhanced recovery of oil and of volatile organic contaminants, and in the geologic disposal of heat-generating high-level nuclear wastes.

This paper presents a critical discussion of different approaches for modeling multiphase flows in fractured media with respect to oil, gas, and geothermal production, and vadose zone hydrology. We limit ourselves to methods that are based on the sound principles and well-established continuum field theories of classical theoretical physics [*Morse and Feshbach*, 1953; *Narasimhan*, 1982a,b] in which conservation of the active system components (water, air, chemical constituents, heat) is expressed by means of integral or partial differential equations (PDEs) for space-and-time varying fields of phase saturations, pressures, temperatures, solute concentrations, etc. Mass and heat fluxes are expressed through phenomenological relationships between intensive variables that drive flow such as multiphase extensions of Darcy's law for phase fluxes, Fick's law for mass diffusion, Scheidegger's hydrodynamic dispersion, and Fourier's law for heat conduction. Alternative approaches such as invasion percolation [*Glass*, 1993], lattice gas automata [*Stockmann et al.*, 1997], and chaos theory [*Pruess et al.*, 1999] have been applied for modeling the detailed spatial and temporal structure of multiphase flows in fractures, but are outside the scope of this article.

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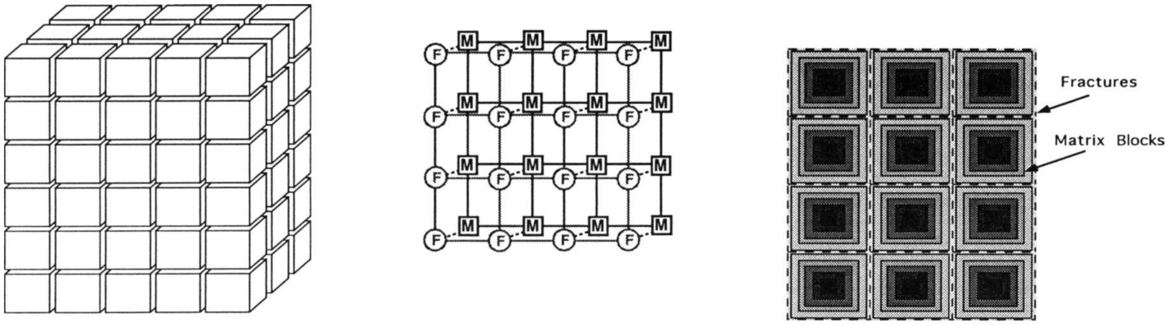
2. VOLUME-AVERAGED CONTINUUM APPROACHES

The study of fractured multiphase flow systems began in the context of oil and gas recovery (for a recent review, see *Kazemi and Gilman*, 1993). The groundbreaking concept on which most later work was based is the "double-porosity" method (DPM), formulated by *Barenblatt et al.* (1960) and introduced into the U.S. petroleum literature by *Warren and Root* [1963]. The basic idea is to associate each "point" in a fractured reservoir domain with not just one, but two sets of hydrogeologic parameters and thermodynamic state variables. Formally this is accomplished by attaching a sphere of "suitable" volume, which contains many fractures, to each point in the reservoir. The volume of the sphere is then partitioned into two subdomains, one for the fractures, the other for



(a) (b) (c)

Figure 1. Illustration of concepts used for modeling of multiphase flow in fractured rocks: (a) double-porosity concept (DPM), after *Warren and Root* [1963], in which global flow occurs exclusively through a network of interconnected fractures, while fractures and matrix may exchange fluids and heat locally; (b) dual permeability model (DKM), with global flow in both fracture (F) and matrix continua (M); (c) MINC subgridding for resolution of gradients in the matrix blocks [after *Pruess and Narasimhan*, 1982, 1985].

unfractured "matrix rock." Volume averages for hydrogeologic data and thermodynamic parameters are considered separately for the two domains. The fractures are viewed as a porous continuum that carries the global flow in the reservoir and is characterized by customary porous medium-type parameters (absolute and relative permeability, porosity, capillary pressure, and compressibility). The matrix blocks provide storage and exchange fluid with the fractures locally. This "interporosity flow" is assumed to be "quasi-steady," occurring at rates that are proportional to the difference in fluid pressures. A schematic illustration of the double-porosity method is given in Figure 1a.

The early double-porosity work emphasized single-phase flow and closed-form analytical solutions, while later developments used numerical simulation to study processes such as water flooding of fractured petroleum reservoirs, where water injected into the fracture system is imbibed into matrix blocks by capillary force, expelling oil [e.g., *Kazemi et al.*, 1976, 1989, 1993; *Thomas et al.*, 1983]. It was recognized that under some conditions, for example in the gas cap of a fractured petroleum reservoir, there may be capillary continuity between matrix blocks, and global flow of the wetting phase may proceed via the matrix continuum [*Firoozabadi and Ishimoto*, 1994]. This led to an extension of the double-porosity approach, commonly referred to as "dual permeability model" (abbreviated "DKM;" Figure 1b), where global flow may occur in both fracture and matrix continua. In some cases the characteristic length of time for fracture-matrix exchange can be very long, so that the "quasi-steady" approximation for interporosity flow is no longer valid. This may occur when fracture spacing is large and/or when diffusivity in the matrix continuum is small. Examples for the latter include systems with tight matrix blocks, multiphase flows with large compressibility and/or large relative permeability changes, heat exchange between matrix and fractures, and diffusive migration of solutes.

When perturbations in the fracture system slowly invade the matrix blocks, it is necessary to resolve the temporal evolution of the gradients (of pressure, saturation, temperature, component concentrations) that drive flow at the matrix-fracture interface. This can be accomplished with the method of "multiple interacting continua" (MINC) [*Pruess and Narasimhan*, 1982, 1985], which partitions matrix blocks into several continua based on the distance of matrix material from the fractures (Figure 1c). Exchange between these matrix continua is usually treated by numerical simulation, although analytical and semi-analytical methods can also be used in certain cases. When implemented through a numerical approach, the MINC method can deal with nonlinear multiphase and non-isothermal processes, as well as with systems in which hydrogeologic properties of the matrix rock may not be homogeneous, but may change as a function of distance from the fractures [*Xu et al.*, 1999].

The double-porosity method and its extensions has primarily been used for studies of oil recovery mechanisms and geothermal production-injection operations in idealized systems, while site-specific modeling of actual fractured reservoirs has usually employed single porous medium approaches. Modeling studies of flow mechanisms have given interesting insights into the interplay between global fracture flow and local fracture-matrix exchange. For example, it was found that there is a general tendency for global flow to compensate for perturbations in local flow, and vice versa, making these types of flow systems "forgiving" in terms of required accuracy of hydrogeologic parameters and numerical discretization schemes. As an example, consider cold water injection into the fracture network of a geothermal reservoir. Let us suppose that the rate at which heat is transferred from the matrix blocks to the fluid near the injection point is underpredicted in a model, either because fracture spacing was chosen inappropriately large, resulting in too small of a heat transfer area, or because of space truncation errors from coarse numerical discretization that underestimates the initially large temperature gradients near the matrix block surfaces. The injected fluid will then have too low a temperature as it sweeps past downstream matrix blocks, which will tend to enhance heat transfer from these blocks, compensating for the upstream errors [*Pruess and Wu*, 1993]. Similar arguments apply for fracture-matrix exchange of fluids or chemical constituents, indicating a relative insensitivity to changes in the fracture-matrix interaction. This has both favorable and unfavorable aspects. It reduces the need for very detailed characterization data, making model predictions more robust, but it also limits the accuracy with which the modeler is able to determine in situ conditions.

3. ABSOLUTE AND RELATIVE PERMEABILITY

For a parallel-plate fracture with aperture b, absolute permeability is $k_f = \frac{b^2}{12}$, so that single-phase flow rate Q for a given pressure gradient is proportional to the cube of the aperture, $Q \propto b^3$ ("cubic law") [*Witherspoon et al.*, 1980]. Many studies have shown that the idealized parallel-plate model is inadequate for understanding flow and transport behavior of fractures on a field scale. The effective fracture aperture as determined from tracer tests can exceed the "hydraulic" aperture derived from pressure drop in viscous flow by as much as 2 to 3 orders of magnitude [*Neretnieks*, 1993]. The large deviation from the cubic law arises from the spatial variability of apertures in real rough-walled fractures. Generally speaking, it is the small apertures (bottlenecks) that control permeability, while it is the large apertures that contribute most to the void volume to be swept by solute tracer. Thus, fracture permeability and fracture aperture, in the sense of void volume per unit fracture wall area, are essentially independent parameters for real rough-walled fractures.

Modeling of multiphase flow behavior with DPM, DKM, or MINC approaches requires specification of absolute and relative permeabilities for a continuum formed by many intersecting fractures. From the mid-60s to the mid-80s the prevailing view in the petroleum literature was that, for fractures, relative permeabilities of wetting and nonwetting phases should sum to 1 regardless of saturation, $k_{rw} + k_{rn} \approx 1$. Often, the even more sweeping assumption was made that relative permeabilities should be equal to the respective phase saturations, $k_{rw} \approx S_w$, $k_{rn} \approx S_n$ (the so-called "X-curves"). These notions about fracture-relative permeabilities can be traced back to laboratory experiments by *Romm* (1966). Romm's experiments used artificial fracture assemblies of parallel plates lined with sheets of celluloid and polyethylene film, or waxed paper, which tended to minimize interference between the flowing phases. Experimental and theoretical work during the last ten years has questioned whether simplistic notions of "fracture-relative permeabilities" are applicable to realistic, rough-walled natural fractures, although the issue remains far from settled at the present time.

Considerable efforts have been made to determine permeability characteristics of individual fractures and of fracture networks in two and three dimensions, for both single-phase [*Long et al.*, 1982] and multiphase conditions [*Pruess and Tsang*, 1990; *Kwicklis and Healey*, 1993; *Karasaki et al.*, 1994]. Studies of individual fractures generally have employed a conceptualization of fractures as two-dimensional heterogeneous media (see below), while the fracture network studies have specified parameters such as spacing, length, orientation, and permeability of individual fractures by means of stochastic distributions. In either case, flow and transport behavior is predicted from postulated geometric characteristics, which conceptually is a very straightforward approach. It should be pointed out, however, that the aspects of fractured media that are most important for flow and transport behavior, namely, fracture connectivity and areal coverage of flow in the fracture plane, tend to be elusive in field observations. It appears that the geometry-based approach is more useful for gaining conceptual insight than for representing flow and transport behavior at specific sites.

The single-phase work has clarified the interplay between geometric characteristics of the fracture network (spacing, length, orientation) and permeability, and the approach to porous medium-like behavior for well-connected networks. The multiphase studies have considered the relative permeability of individual fractures, or fracture networks, to two phases flowing simultaneously. It was found that interference between phases is strong, causing the sum of wetting and nonwetting phase-relative permeabilities to be small at intermediate saturations [*Pruess and Tsang*, 1990]. This was confirmed in laboratory experiments [*Persoff and Pruess*, 1995], and is consistent with insights gained from percolation theory for the connectivity of two-dimensional lattices. However, the issue of "fracture-relative permeabilities" remains controversial. In a recent paper, *Horne et al.* [in press] presented steam-water flow experiments in fractures assembled from roughened glass plates, and stated that observations could only be matched by simulation when X-curve relative permeabilities were used.

Most theoretical and experimental studies have examined individual fractures on a relatively small scale, and their practical implications are not clear. For field-scale flow processes it is conceivable that the wetting phase may flow in the "small" fractures and the nonwetting phase in the "large" fractures, with minimal phase interference. In other words, the problem of two-phase flow in individual fractures may not be relevant to multiphase flow behavior in a field-scale fracture network. Simultaneous flow of two phases in a single fracture, if it does occur, may take place primarily at high rates in large fractures that feed wellbores; the quasi-static capillary-based phase occupation scheme postulated in the mathematical modeling of fracture-relative permeability may not apply for these conditions. For water seepage through fractured unsaturated zones, permeability itself may be an irrelevant parameter. In fact, it has been shown that in unsaturated fractured media the rate at which seeps advance downward may be larger in media with a smaller average permeability (see below).

4. HIGH-RESOLUTION FINITE DIFFERENCES

In thick unsaturated zones in fractured rocks of (semi-) arid regions, water seepage may proceed through highly localized preferential pathways. In such systems, much of the fracture volume does not participate in flow and large-scale volume averages may be completely meaningless. Continuum approaches may still be applicable to these systems, however, if applied on the actual scale where the flow processes occur. A key concept that has provided much useful insight into multiphase flow behavior is the view of fractures as "two-dimensional heterogeneous porous media." This conceptualization comes in two "flavors," a more microscopically oriented one in which a fracture is described in terms of a spatially variable aperture, and a more macroscopic model in which a fracture is represented by means of spatially variable permeability. The description in terms of apertures is appropriate for fundamental studies of flow on small spatial scales (on the order of 10^{-3} to 10^{-1} m). When using this approach investigators have either attempted to approximately solve the Navier-Stokes or Reynolds equations in the irregular pore space [*Brown*, 1987; *Glover et al.*, 1998], or have introduced the simplifying assumption that the fracture can be represented locally by a parallel plate model, so that flow can then be described by Darcy's law [*Pruess and Tsang*, 1990].

For flow processes on a somewhat larger scale, fractures are discretized into subregions of order 0.1 m or larger, and the customary continuum concepts of absolute and relative permeability and capillary pressure are applied [*Pruess*, 1998]. Justification for this is provided by laboratory experiments that have shown that, for "slow" flows in "small" fractures, continuum concepts are indeed applicable on a scale of order 0.1 m [*Persoff and Pruess*, 1995]. An areally extensive fracture is modeled as consisting of spatially correlated subregions with different permeability and capillary pressure characteristics (Figure 2). Aspects of heterogeneity in the fracture plane that are believed to be essential for replicating natural features include (a) regions of zero permeability, representing asperity contacts where the fracture walls touch; (b) a more or less gradual change towards larger apertures away from the asperities; (c) finite spatial correlation length for permeability; and (d) nonzero irreducible water saturation, representing water films held by capillary force in fracture wall roughness [*Tokunaga and Wan*, 1997]. In the continuum approach, effects of water held by capillarity and adsorption on fracture walls can be modeled by means of appropriate relative permeability and suction pressure relationships.

Simulation studies of water seepage in synthetic fractures with highly resolved heterogeneity have produced useful insights into hydrogeologic mechanisms in thick unsaturated zones in fractured rock. Fracture flow was found to proceed not in smooth sheets, but in dendritic patterns along localized preferential paths, giving rise to such features as ponding and bypassing (Figure 2). As long as fluxes are small compared to saturated hydraulic conductivity, unsaturated seepage may be dominated by flow funneling into localized pathways, due to subhorizontal barriers that may be formed by asperity contacts or fracture terminations. Flow funneling effects and localized seepage flux will increase with increasing length of subhorizontal barriers, while average vertical fracture permeability, as could be measured by monitoring

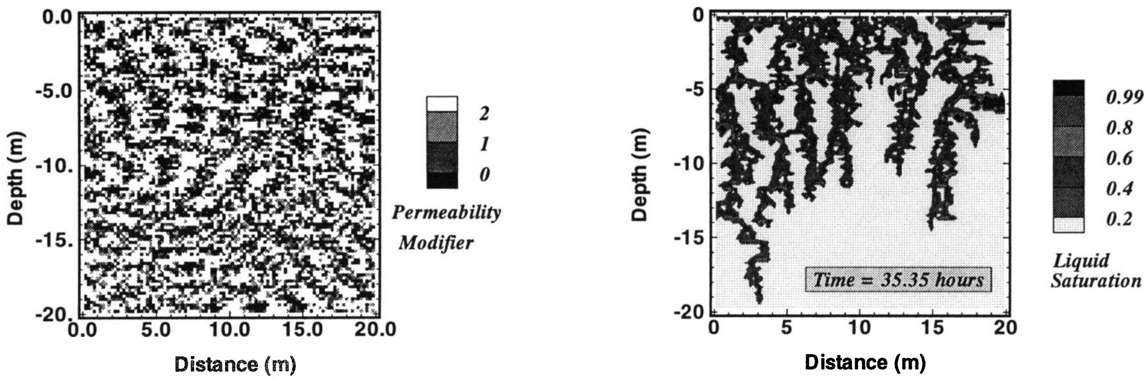


Figure 2. Stochastic permeability field (left) and seepage pattern (right) at the time of breakthrough at a depth of −19.5 m for water injection at a constant rate of 10^{-3} kg/s over the entire top of the fracture.

the propagation of gas pressure disturbances, would decrease [*Pruess*, 1999]. This is illustrated in Figure 3, which shows simulated saturation distributions for water injected uniformly over a 10-m-wide region at the top of a subvertical fracture (tilt angle of 80°). For a homogeneous fracture, water breakthrough at a 100-m depth occurs after 456.0 days. When a sloping impermeable obstacle is introduced into the fracture, flow is funneled into a narrow region, resulting in larger fluxes and accelerated breakthrough. At the same time, average permeability in the vertical direction becomes smaller when a longer obstacle is placed into the fracture. Thus, we have the remarkable situation in which unsaturated seepage can actually proceed faster in media with a lower average permeability (Figure 4). This seemingly paradoxical result emphasizes aspects that are unique to unsaturated flow in fractured media, and suggests that "average permeability" may not be a meaningful parameter for this process.

WATER INJECTION INTO VAPOR-DOMINATED GEOTHERMAL RESERVOIRS

Extensive steam production from the fractured vapor-dominated geothermal reservoirs at Larderello, Italy, and The Geysers, California, has caused a decline of reservoir pressures and well flow rates, and has led to an underutilization of installed electric generating capacity. These reservoirs are beginning to run out of fluid, while heat reserves in place are still enormous. Vapor-dominated geothermal reservoirs are naturally water-short systems. Fluid reserves tend to get depleted during exploitation much more quickly than heat reserves. Injection of water is the primary means by which dwindling fluid reserves can be replenished, and field life and energy recovery be enhanced.

Injection of cold water into homogeneous porous vapor zones entails rock-fluid heat transfer on a local (grain) scale, which is a rapid process, so the approximation of instantaneous local equilibrium between rocks and fluids is well justified. The process involves partial vaporization of the injected water and gives rise to two sharp fronts, a phase front at a temperature T_f, less than original reservoir temperature T_{res}, where conditions change from single-phase liquid to superheated steam and, closer to the injection point, a thermal front at which the temperature jumps from injection temperature T_{inj} to T_f [*Pruess et al.*, 1987]. When cold water is injected into hot fractures, heat transfer from the rocks to the fluids occurs slowly (conductively). Instead of sharp fronts, we then obtain very broad zones where fluid temperatures and saturations change gradually. In subvertical fractures, injection plumes evolve through a complex interplay of heat transfer, boiling and condensation phenomena, gravity effects, and two-phase flow. Vaporization dominates in the hotter portions of the plume, away from the injection point, while vapor tends to flow towards cooler lower-pressure regions near the injection point where it condenses. The counterflow of liquid away from the injection point and the flow of vapor towards it constitute a very efficient heat transfer system known as heat pipe, which tends to diminish temperature variations throughout the injection plume. Because vapor has a much lower density than liquid water, it has larger kinematic viscosity and acts as the more viscous fluid. Very considerable vapor pressure gradients may be generated during vaporization, which may be comparable in magnitude to a gravitational body force on the liquid, providing a mechanism for lateral flow of liquid, with associated potential for early breakthrough at neighboring production wells [*Pruess*, 1997].

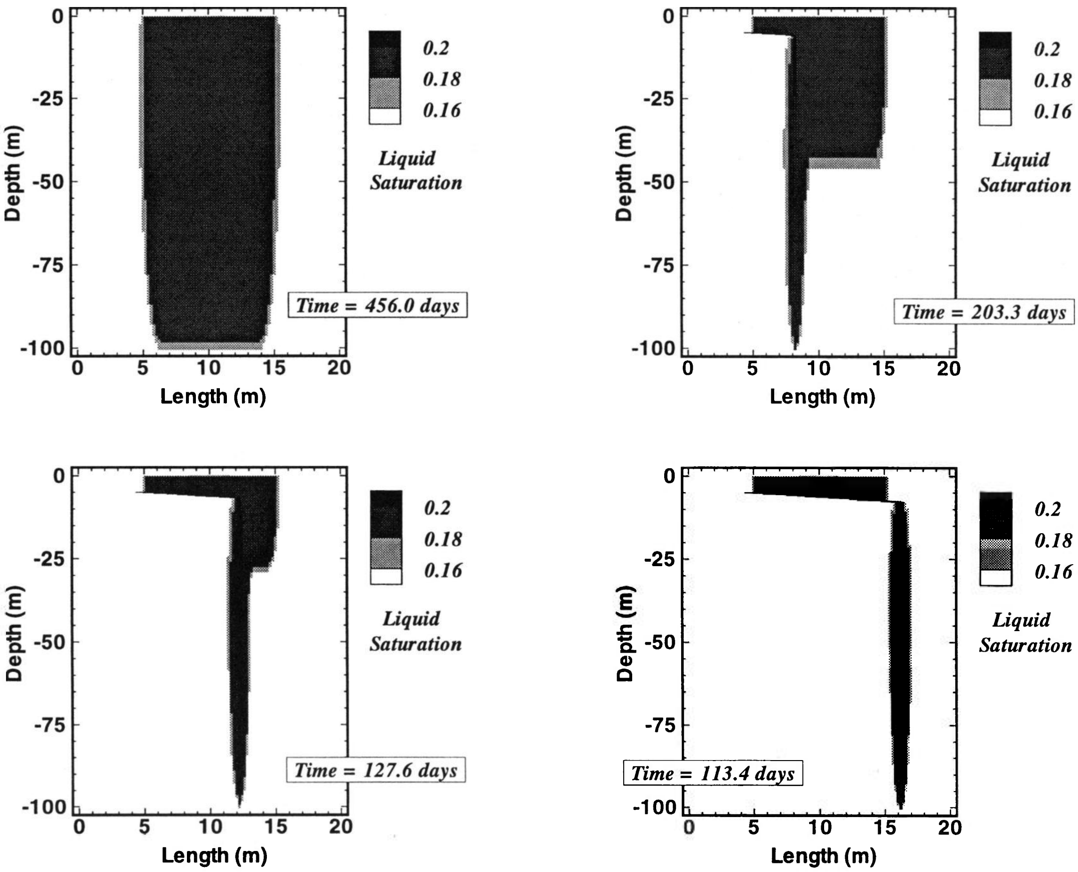


Figure 3. Simulated water saturations at time of breakthrough at a –100-m depth for seepage in subvertical (80°) homogeneous fractures with a single embedded subhorizontal obstacle of rectangular shape and variable length. The impermeable obstacle starts at the left boundary at a depth of –4 m and slopes downward to the right at an angle of 14.0°. Different cases were simulated in which the length interval blocked by the obstacle was l = 0 (no obstacle, top left), l = 8 m (top right), l = 12 m (bottom left), and l = 16 m (bottom right).

6. NUCLEAR WASTE DISPOSAL

Mathematical models have been extensively used in investigations of the thick (≈600 m) fractured vadose zone at Yucca Mountain as a potential site for a high-level nuclear waste repository. Numerical simulations of flow and transport at Yucca Mountain have generally emphasized large-scale spatial averages, and have employed fracture continuum approaches, such as DPM, DKM, MINC, and single effective continuum models (ECM) [*Wu et al.*, 1999]. High-resolution models with explicit discretization of fractures have also been used to study basic mechanisms of fluid and heat flow in this unusual hydrogeologic environment [*Birkholzer and Tsang*, 1998]. Large-scale volume-averaged models have been very successful at describing the propagation of barometric or artificial pressure pulses, and for describing temperature evolution during heater tests. Gratifying as this success is, it is not unexpected. This is because gas flow and heat conduction, being described by parabolic partial differential equations, are subject to strong internal averaging mechanisms. Water seepage in fracture networks at rates far below saturated hydraulic conductivity, however, is described by a hyperbolic PDE. In this case internal averaging mechanisms are essentially absent, and volume averages are not enforced through physical processes in the flow system, but are formal constructs of the analyst. Predictions of water seepage from volume-averaged continuum models must therefore be interpreted with a great deal of caution.

Recent observations of environmental tracers at Yucca Mountain have provided direct evidence that water can

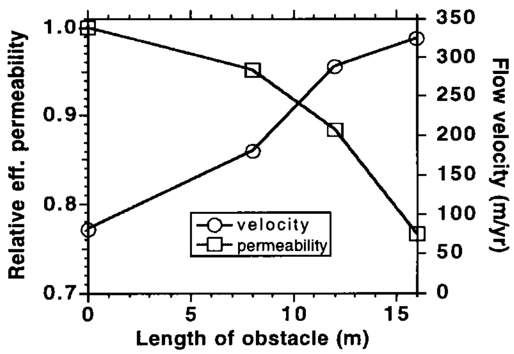


Figure 4. Average flow velocity for seepage in fractures with embedded obstacles of different length, as shown in Figure 3. Effective vertical permeability for single-phase flow is also plotted, and is seen to decrease with length of obstacle, while average water seepage velocity increases.

flow through unsaturated fractured rocks over vertical distances of several hundred meters at velocities of an order of 10 m/yr or more [*Yang et al.*, 1995; *Fabryka-Martin et al.*, 1996]. These observations came as a surprise to many, even though early work by U.S. Geological Survey scientists had suggested that the well-connected fracture network at Yucca Mountain would provide pathways that could rapidly drain away episodic infiltration [*Roseboom*, 1983]. Capillary theory would appear to suggest that the strong suction from the unsaturated rock matrix, of order $P_m \approx -3$ bar, at Yucca Mountain [*Rousseau et al.*, 1997] would quickly remove free water from the fractures, making it difficult to understand "how fractures could remain sufficiently saturated to act as fast paths in the face of high matrix suction" [*Cook*, 1991]. Matrix imbibition indeed would be a very strong process if water were flowing down fractures in the form of area-filling sheets [*Nitao and Buscheck*, 1991]. However, recent mathematical modeling has demonstrated and quantified several mechanisms that could drastically diminish water imbibition into the rock matrix, including (1) funneling of flow into localized preferential pathways, which reduces the wetted area where imbibition occurs; (2) the episodic nature of infiltration, which reduces the time available for removing water from the fractures; and (3) mineral coatings on fracture walls, which reduce imbibition fluxes. Based on numerical simulation experiments, it was suggested that the total wetted fracture-matrix interface area is comparable in magnitude to the land surface area beneath which it is present, and that spacing between major localized seeps may be on the order of 50 m or more [*Pruess*, 1999]. Flow of liquid films held on rough fracture walls may provide a mechanism for fast transport [*Tokunaga and Wan*, 1997], but total percolation flux carried in films is expected to be very small under the suction conditions that prevail at Yucca Mountain [*Pruess*, 1999].

Emplacement of heat-generating high-level nuclear wastes in thick unsaturated zones of fractured tuff at Yucca Mountain would give rise to complex multiphase fluid flow and heat transfer processes. For strongly heat-driven flows, water held in tight matrix pores will be vaporized as temperatures approach and exceed the boiling point at ambient pressures. The resulting pressurization will expel vapor from the matrix, which subsequently will flow away from the heat sources in the fracture network. Upon encountering cooler wall rock, the vapor will condense. The condensate will flow in the fractures under the combined action of gravity, pressure, and capillary pressure forces, and be partially imbibed into the rock matrix. Numerical simulations of this process using simplified geometric descriptions, large-scale volume averaging, and more or less homogeneous media have predicted that over time the rock in the vicinity of the heat sources will dry out [*Buscheck and Nitao*, 1993; *Pruess and Tsang*, 1993]. This observation has led some workers to propose a repository concept called "extended dry," in which high thermal loading would be used to effectively protect waste packages from being contacted by liquid water. However, critics have pointed out that liquid water can migrate considerable distances through fractured rock that is at above-boiling temperatures and be only partially vaporized [*Pruess and Tsang*, 1994; *Pruess*, 1997]. An added concern is that large repository heat loads would increase rates of vaporization and condensate formation, thereby promoting nonequilibrium matrix-fracture flow effects that could enhance localized and intermittent water flow near the waste packages.

7. SCALING RELATIONSHIPS

Laboratory experiments using transparent replicas of natural rock fractures, or artificial fracture assemblies made from materials such as roughened glass plates, have provided much useful qualitative and quantitative insight into multiphase flows under ambient conditions [*Su et al.*, 1999], as well as under thermal drive [*Kneafsey and Pruess*, 1998]. However, the significance of flow phenomena on a laboratory scale for the much larger spatial dimensions in field-scale problems is uncertain. Mathematical models can be very useful for evaluating relationships between flow processes on different space and time scales. Let us consider a plane heterogeneous fracture, with coordinates x in the horizontal and z in the (sub-) vertical direction. Applying the following simultaneous transformation of space and time coordinates

$$\begin{aligned} t &\rightarrow t' = \lambda_t \cdot t \\ x &\rightarrow x' = \lambda_x \cdot x \ , \\ z &\rightarrow z' = \lambda_z \cdot z \end{aligned} \tag{1}$$

it can be shown that the Richards' equation for unsaturated flow in the fracture remains approximately invariant when

$$\lambda_t = \lambda_x^2 = \lambda_z \, . \tag{2}$$

Rates of external sinks/sources scale by λ_x. Thus, (sub-) vertical-length scale and time need to be stretched by the square of the horizontal scale factor. The validity of the scaling invariance given in Equation (2), as well as its limits of applicability, were confirmed by numerical simulation [*Pruess*, 1998]. It is even possible to obtain an approximate scaling invariance for vaporizing water flow down hot rock fractures. In addition to the relations given in Equation (2), this requires scaling of the thermal diffusivity of the wall rock by a factor $\lambda_\theta = 1/\lambda_z$. It may appear as though this approximate scaling invariance has little practical value, involving as it does a scaling of thermal diffusivity, which for rocks is a material parameter with little if any systematic dependence on scale. However, vaporization behavior in a "large" rock fracture in the field could be replicated through smaller-scale experiments in the laboratory if different fracture wall materials with larger thermal diffusivities were used. For example, the thermal diffusivity of cast iron is approximately 10 times larger than that of typical hard rocks, so that vaporization and flow behavior in a laboratory fracture of $x = 1$ m, $z = 1$ m size in cast iron should be similar to that of a rock fracture of $x = \sqrt{10} = 3.16$ m, $z = 10$ m size with a 3.16 times larger water injection rate and a 10 times slower time scale.

8. CONCLUDING REMARKS

Fractured flow systems have received increasing attention during the last several decades. They exhibit a tremendous diversity of fracture and rock matrix properties and flow and transport processes. Early work emphasized applications to oil and gas reservoirs and large-scale volume averaged approaches. More recent studies have often been motivated by applications related to waste disposal, and to environmental protection and remediation, which typically involve higher spatial resolution of small-scale processes. Depending on the nature of the fractured flow system under study, and the engineering or geoscientific interest and purpose in dealing with the system, different approaches will be employed for characterization and modeling. It is well to remember that models represent idealizations and simplifications of real systems, and their formulation (governing equations, system parameters) typically is valid only for certain space and time scales, and for a limited range of physical, chemical, etc., conditions. These limitations are seldom made explicit in the formulation of models; in fact, they may often be poorly known. At best, mathematical models may be able to identify and quantify the key processes and parameters that determine the behavior of the flow system under study, for the conditions and space and time scales of interest to the analyst. For a mathematical modeling effort to be successful, perhaps the single most important prerequisite is to have very clear and specific objectives.

Most modeling approaches rely on volume averaging to some extent. This works well for systems in which physical averaging mechanisms are present, usually described by parabolic partial differential equations (PDEs). This includes diffusive processes such as heat conduction, gas flow in unsaturated zones, capillary-driven liquid flow, and molecular diffusion of solutes. Volume averaging can generate misleading results when internal averaging mechanisms are absent or weak (hyperbolic PDEs), as in episodic water seepage through highly permeable fracture networks in thick unsaturated zones. The absence of internal averaging mechanisms greatly complicates flow modeling.

Much useful insight into multiphase flow behavior and mechanisms in fractured formations has been gained through the study of idealized systems. Examples include oil recovery from fractured reservoirs through water- and steam-flooding, injection of cold water into fractured geothermal reservoirs, and water seepage in unsaturated rock fractures. Applications to site-specific predictive modeling have been more difficult to achieve, as they raise difficult issues of characterization and model calibration, and applicability of conceptualizations for processes operating on different space and time scales. A general problem with modeling of flow in fractured media arises from the geometric complexity of individual fractures and fracture networks. Fracture geometry on different scales is a very natural starting point for flow and transport modeling, but geometric features that are crucial for flow behavior, such as fracture connectivity, are very difficult to determine in the field.

The presence of fractures generally makes flow and transport behavior more complex than it is in homogeneous porous media, but fractures also allow for some unique simplifications. For example, flow in "small" fractures in hard rocks with low matrix permeability is essentially a two-dimensional process. Compared to three-dimensional porous media, flows in two-dimensional heterogeneous fractures are more easily modeled mathematically and are more amenable to direct observation and visualization on a laboratory scale. Thus, fractures can provide convenient systems for learning about flow in more general heterogeneous porous media.

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