A Review on Fluid Dynamics of Fractured Reservoir Geology

G. Suresh Kumar*

Abstract**—** This manuscript provides a review on fluid dynamics of subsurface flow in a heterogeneous fractured reservoir at the scale of a single fracture. The primary focus of this work is to discuss a few points on the general sub-surface fluid dynamics in the context of fractured rock hydrogeology. A second focus is on the computational fluid dynamics aspects of non-isothermal reactive solute transport related to dual-porosity approach.

Keywords**—**Fluid dynamics, Fractured reservoir, Single fracture, Solute transport, Numerical complexities.

I. INTRODUCTION

The peninsular India, occupying roughly a third of India, is predominantly composed of low permeability hard-rocks such as igneous and metamorphic rocks and consolidated sedimentary formations. Such geological formations, particularly rock masses, are different from unconsolidated porous media in the sense that they are often fractured. Such fractured geologic materials are examples of highly heterogeneous systems because of the very large contrast in material properties, such as permeability and specific storage, between the high permeability fractures and the surrounding low permeability rock matrix. Hence, flow and transport through fractured porous media can be quite different from flow and transport through unfractured porous media. Heterogeneity in flow and transport properties also exists (a) within single fractures, (b) between the numerous fractures that form a complex fracture network and (c) within the rock matrix surrounding the fractures. This high level of spatial variability in flow and transport properties greatly complicates field characterization of fractured systems. It also increases uncertainty in the knowledge of these systems and affects the type of flow and transport model that is applicable. Although great advances in model capabilities have been made in recent years, the development of numerical models to simulate fluid flow and solute transport still remains an active area of research in fractured rock hydrogeology.

Deep seated fractured porous media of low permeability formations called hard rocks are generally used to receive scarce attention because they lacked interest for water supply. However, a large effort has been devoted to the characterization of these materials during the last 30 years because of their potential for waste isolation. The prospect of storage and disposal of radioactive and toxic chemical wastes in fractured low-permeability geologic media, on the fluid flow and solute transport properties of fractures, has become an area of large interest in the last few decades, because of various national and international efforts in studying the final disposal of radioactive wastes from nuclear power plants. Until recently, studies of non-reactive tracer movement in porous formations exhibiting heterogeneity due to variation in hydraulic conductivity have been the subject of considerable research over the past several years. In these studies focus has been on understanding the effective values of solute velocity and macro-dispersion since these properties have a major influence on pollutant migration in an aquifer with regard to both dilution of concentrations and first-arrival times of solute at a given location.

Transport through fractured rocks deals with special kind of heterogeneity, where the permeability of fractures differs markedly from the rest of the rock matrix. The intricate geometry of the fractured porous medium leads to complex fluid velocity profiles. These complex velocity profiles result in the mixing of transported quantities such as mass and heat. For example, the movement and mixing of solutes in fractured media is of particular interest in an environmental context because of the possibility of very rapid and extensive movement of contaminants through fractures, cracks, or fissures in otherwise low-permeability rock. Since, the flow velocities in the fracture are generally significantly faster than the flow in porous rock matrix lead to the potential for mass and heat to be transported through the medium relatively quickly. In the context of contaminant transport, this can have negative consequences. In addition to the large velocity gradient between fracture and solid rock matrix, other physical and chemical processes can inhibit or enhance the rate of transport. In particular, heat exchange and chemical reactions can have a tremendous effect on the transport process. In the case of mass transport, the particles may react with other particles in the fluid or with the particles that make up the fracture surface. In addition, they may diffuse into the rock matrix and react with the solid surfaces in the matrix. Moreover, heat exchange and chemical reactions at the solid surfaces of the porous media can significantly influence the nature of the flow and transport processes. A practical example of a situation that embraces all these features is the leaching of radioactive contaminants from a nuclear waste repository located in fractured granite rock. Several countries including India are planning to build, or building, repositories in

* Associate Professor, Petroleum Engineering Program, Department of Ocean Engineering, Indian Institute of Technology – Madras, Chennai – 600036, E-Mail: gskumar@iitm.ac.in

fractured geological formation. The most notable of these are the Grimsel site in Switzerland and the Yucca Mountain site in Nevada. Thus, a basic understanding on fluid-rock interaction between high permeability fracture and low permeability rock matrix becomes critical at the scale of a single fracture. For this purpose, numerical modeling acts as an excellent artifact as against the hazardous, expensive, and time-consuming laboratory and experimental methods. In addition, since a fractured rock formation has a special kind of heterogeneity, field experiments in such formations remain rare, while numerical modeling is yet to strike a balance between physical continuity (deducing a meaningful Representative Elementary Volume as the flow variables remain discontinuous over fracture-matrix interface) and mathematical continuity (where the flow variables by default are supposed to smooth and continuous). This is because the pore scale physical processes occurring within void (fracture) or solid-grains (rock-matrix) have disproportionate geometries of length dimensions varying over several orders of magnitude, unlike observed in a classical porous medium, and eventually up-scaling in such a medium is not straight forward, and deserves a special attention towards numerical modeling. Hence, a basic understanding on the fluid dynamics becomes inevitable to appreciate the numerical complexities associated with computational fluid dynamics. This manuscript has made an attempt to discuss on some of the issues on basic fluid dynamics and its associated computational fluid dynamics aspects arising from fracture-matrix coupling at the scale of a single fracture in a fractured reservoir.

II. FLUID DYNAMICS

A. *Hydrogeology*

To have a better understanding on the dynamics of fluid flow in a fractured reservoir, it is better to have a basic understanding on the geological setting of a structurally complex fractured reservoir. A good geological model having details on rock types, geologic mapping, topographic conditions, etc. form the basis for a conceptual groundwater flow model as it provides an idea about the origin and direction of groundwater flow along with the information on vulnerability of water supply to contamination. Given various rock types, extrusive igneous rocks (for example, basalt, andesite and rhyolite) have a relatively greater Storativity and Transmissivity than that of its intrusive nature. Such igneous rocks and also sedimentary rocks get transformed by recrystallization into a new form called “metamorphic rocks” under deeper depth, where temperature and pressure are expected to be very high. In general, as the depth increases, the basic aquifer properties namely porosity and permeability decreases. Off the three rock types, sedimentary rock is assumed to predominantly consist of water (groundwater) and/or oil (petroleum) bearing contents. In such rock types, primary porosity and/or permeability is the main fluid storage space, while igneous and metamorphic rocks have insignificant primary porosity and any fluid storage and/or transmission is only by secondary porosity and/or permeability such as a fracture.

While porous medium is solely described by primary porosity, which is formed at the time of formation, [1] described three types of porosities for a fractured reservoir namely primary inter-granular porosity in solid rock matrix, secondary fracture porosity along high permeable fracture, and the secondary/tertiary micro-fracture porosity within the low permeability solid rock matrix. A couple of decades later [2] classified fractured rock aquifers into four different types based on the earlier porosity classification. Type 1 being purely fractured rocks, there is no exchange of fluid mass between fracture and rock-matrix and the fractures act as conduits. Types 2 and 3 being fractured formation and doubly porous rock respectively there exist a definite fluid mass transfer between the geological units of significantly varying hydraulic conductivities and storativities. Types 2 and 3 are typically characterized by the presence of two distinct of homogeneous geological units resulting from two distinct hydraulic potentials, one each for fracture and rock-matrix. Type 4 being a heterogeneous formation, the distinction based on hydraulic conductivity and storativity between fracture and rock-matrix is marginal and the entire rock mass can be treated as a single continuum as against the dual continuum. In other words, Type 4 can be treated as an equivalent continuum model using conventional Representative Elementary Volume (REV) concept.

A very recent phenomena on shale gas reservoir poses yet another dimension of complex hydrogeology, where gas is produced in association with substantial volumes of water. [3] defined an unconventional reservoir as a reservoir with significant regional extent; with a significant hydrocarbon reserves in place; with a low recovery of hydrocarbons (10 – 15%); a very low matrix permeability (10 – 100 nano-Darcy); and without conventional hydrocarbon trapping mechanism. The pore sizes in such formations generally vary between 0.5 – 100 nano-Meter). These shale gas reservoirs have fluids not only in pore spaces but also on the surfaces of solid particles [4]. Further, computational findings of permeability impairments and its associated fracture closure, resulting from swelling tendency of shale formation, which are related with hydration stress and overburden pressure are difficult to achieve. Thus, in shale gas reservoirs, in addition to the geological complexities, the fluid flow through these tiny pores becomes extremely complex as it involves the sorption kinetics of fluid molecules, and eventually affects the fluid flow rate.

B. *Concept of Continuous Fluid Flow*

The very statement of “continuous fluid motion” is valid only at a larger scale, and not, at its molecular scale. The movement of a particle (and not parcel) at its molecular scale is highly discontinuous, and hence, conventional calculus cannot be applied to analyze the fluid behavior as the fundamental assumption involved in calculus requires that the function of interest must be smooth and continuous. Hence, fluid parcels (a cluster of fluid particles in a considered volume element) are preferred for fluid analyses instead of point masses. The volume of such fluid parcel should be chosen in such a way that it should be significantly small in comparison with the characteristic length of reservoir, while it is significantly large enough with respect to the individual fluid particle size so that a representative mean value can be arrived over the volume of interest known as Representative Elementary Volume (REV). Thus, fluid parcels are assumed to be in a continuous motion in continuum mechanics, and this macroscopic continuous fluid flow represents the fluid flow resulting from collective fundamental types of fluid displacements namely translation, rotation, linear strain (deformation), and shear strain (deformation). Further, since, fluids do not have tension and have only pressure or compression as the normal stress in addition to tangential shear stress, the concept of rate of deformation is used for fluids as against the deformation concept that is conventionally used in solids. In other words, since shear strain cannot be measured for fluids, the concept of shearing modulus cannot be assigned for fluids, and instead, the concept of bulk modulus, which is the reciprocal of compressibility, is generally used for fluids. However, the concept of shear stress still plays a crucial role in defining the viscosity of a fluid, and this stress contributes to the viscous dissipation of mechanical energy to heat. In other words, viscosity of a fluid assigns the shear stress needed to maintain a given velocity gradient within a fluid.

The mathematical description of fluid flow involves the spatial and temporal distribution of dependent variables such as density, velocity and pressure either by Eulerian or Lagrangian description. It can be noted that in an Eulerian approach, the spatial location refers to a fixed position and it does not change with time. And hence, derivative of a spatial location with respect to its time has no physical relevance in an Eulerian approach, while the same represents the mean velocity of a moving fluid parcel. Thus, with regard to variables, the value of the dependent variable does not change with time for a steady flow, while the value of the independent variable does not change with time in an Eulerian description.

C. Energy Considerations

When the fluid flow is laminar in a fully saturated geological formation, the kinetic energy per unit weight of fluid is generally considered to be insignificant. However, in preferential flow paths along the fractures in a fractured reservoir, the assumption of laminar flow may not always be valid as the discharge rate is directly proportional to the cube of void (or fracture aperture) and not to the square of void (mean grain size diameter).

In a petroleum reservoir system, since the concept of relative permeability prevails predominantly due to the immiscible (for example, oil and water) fluid flow, all fluid particles particularly at the fluid-fluid interface may not be able to move with the same fluid velocity and the resulting kinetic energy may not be straight forward to compute as it is done for a single phase fluid flow. In addition, during the oil production, although the specific gravity of immiscible fluids can be kept constant, their respective volume expansion cannot be treated to be insignificant. During oil production, although the specific gravity of immiscible fluids can be kept constant, their respective volume expansion cannot be treated to be insignificant, and hence, the value of kinetic energy deduced as a function of fluid mass and mean velocity may not be valid. It can be noted that the velocities of different fluid particles emanating from two different immiscible fluids cannot be integrated directly to deduce the actual kinetic energy, particularly at the fluid-fluid interface. In addition, since, the fluid velocities at the respective immiscible fluid boundaries have a common fluid-fluid interface, the axial components of velocity cannot acquire the velocity of a solid body (no slip condition), and in turn, the concept of kinetic energy correction factor becomes fuzzy in a petroleum reservoir system. A fluid parcel of weight W located at a height h above datum possesses a potential energy of $(W\,x\,h)$ and the respective potential energy per unit weight is W. In the context of a petroleum reservoir system, although the Oil-Water contact may change with time, W may not get affected as h represents the difference in elevation. Considering the role of thermodynamics in the context of reservoir engineering, the internal thermal energy, which is primarily a function of temperature, also depends on specific volume or pressure, when the liquid hydrocarbons approach the gaseous phase.

Regarding groundwater movement, based on Dupuit-Forchheimer assumption, the groundwater flow needs to be parallel to the groundwater table, while the flow direction is dictated by the slope of the groundwater table. For example, the direct implication of such assumption may be easily understood from the consideration of specific yield to be equivalent to that of an effective porosity. However, it may be noted that specific yield results from drainage in the vertical direction resulting from gravitational pull, while effective porosity value is meant for groundwater fluid flow in a horizontal direction. In addition, from Darcy's law groundwater flow needs to be along the direction of the pressure gradient. However, [5] described the groundwater fluid flow as a function of gravitational potential as well in addition to the conventional consideration of pressure potential only. In essence it was concluded that groundwater flows from points of higher potential energy to lower potential energy and the flow can occur in any spatial direction. This potential energy called the fluid potential is a function of hydraulic head. Since the fluid mean velocity in a sub-surface system is assumed to be insignificant, the kinetic energy is ignored, and the hydraulic head has only two components namely pressure head and gravitational head. Due to the hydraulic resistance offered by the solid grains to the groundwater fluid movement, the aquifer system as a whole tends to minimize its overall energy potential. Since, the concept of control volume is the virtual volume introduced in an Eulerian approach to describe the dynamics of fluid flow, the concept of conservation of mass within the control volume becomes the basis for fluid analysis. It can be noted that while expressing the non-conservative form of mass conservation equation, the material derivative may not be insignificant as the density differences found in geothermal reservoirs under elevated temperature and in petroleum reservoirs under elevated pressure and temperature may be significant.

III. IDEALIZED FRACTURED RESERVOIR

It was [6] who first explained the concept of hydraulic diffusivity in order to describe fluid flow through a heterogeneous fractured reservoir, which essentially consists of high permeable matrix blocks separated by high permeable fractures. Since [6] provided solutions for particular cases, [7] - [11] provided solutions for fractured reservoirs with infinite fracture extent, while [12] – [15] provided solutions for a fracture with finite extent. Exchange of fluid mass between fracture and matrix being the highlight of an idealized fractured reservoir at a local scale, few researchers assumed this mass transfer to be instantaneous {[6] – [9]}, [16] raised concerns over this theory, and provided a transient theory to describe the fluid mass transfer between fracture and rock-matrix. Since all these approached considered the rock mass as a system a well defined two different homogeneous geological units, the practical applicability of this approach had its own limitation. To circumvent this problem, researchers tried to model the field scale complicated fracture network of rock masses. Since statistical characterization of such fractured rock parameters such as fracture length, aperture size distribution, fracture spacing, fracture density and fracture orientation was extremely difficult, the application of stochastic modeling also had a limited usage to understand the fluid dynamics of heterogeneous fractured rocks. However, [17] projected the positive aspects of geo-statistical approach in describing the fluid dynamics of fractured reservoirs.

IV. COMPUTATIONAL FLUID DYNAMICS

Computational Fluid Dynamics in the context of reservoir engineering represents the forces exerted by or upon, real mobile gaseous and/or liquid hydrocarbons in a saturated geologic formation in order to deduce the pressure distribution profiles with the use of computers using varieties of numerical methods. Despite the coupling between classical hydrodynamics, which is associated with an ideal inviscid fluid flow, and empirical hydraulics, which is confined to single phase real fluid flows, the fluid dynamics of a petroleum reservoir system remains complex as it is associated with multi-phase fluid flows under elevated temperature and pressure. The problem becomes further complex as the volume of gaseous and liquid hydrocarbons is greatly affected by changes in reservoir pressure and/or temperature. This volume change leads to a density (reservoir fluid property) change, and in turn, the concept of incompressible fluid flow in a petroleum reservoir system becomes highly questionable. In addition, since the viscosities of liquid hydrocarbon drops down with temperature (due to the decreasing cohesive force), while the viscosities of gaseous hydrocarbons enhances with temperature (due to an increased molecular activity), the resulting relative permeability, and in turn, the mobility of hydrocarbon fluids at a particular temperature is highly approximated.

In addition, since a fractured rock formation has a special kind of heterogeneity, field experiments in such formations remain rare, while numerical modeling is yet to strike a balance between physical continuity (deducing a meaningful Representative Elementary Volume as the flow variables remain discontinuous over fracture-matrix interface) and mathematical continuity (where the flow variables by default are supposed to smooth and continuous). This is because the pore scale physical processes occurring within void (fracture) or solid-grains (rock-matrix) have disproportionate geometries of length dimensions varying over several orders of magnitude, unlike observed in a classical porous medium, and eventually up-scaling in such a medium is not straight forward, and deserves a special attention towards numerical modeling.

While the concept of Computational Fluid Dynamics (CFD) plays a significant role in describing the fluid flow through a classical porous system as well as in a fractured reservoir, the application of CFD to a geological formation having very low porosity as well as permeability such as shale gas reservoir becomes a question. The conventional Darcy's law and Cubic Law reasonably describe the fluid flow through porous media and a fractured reservoir, there is no well defined equation to understand the fluid dynamics in very tight formation such as shale gas reservoirs. Since, the intrinsic permeability values fall in the range of few nano-Darcies, the applicability of conventional fluid flow equations using Darcy's or Cubic law becomes questionable. Further, the presence of very small pore sizes in the range of a few nano-Meters makes the fluid very difficult to get advected. Rather, the fluid dynamics is well defined by diffusive processes. For computational purposes, deducing an effective diffusion coefficient becomes a challenging task as the fluid dynamics may be defined either by surface diffusion or by Knudsen diffusion depending on the pore size. The next level of complication arises from the sorption kinetics resulting from differing rate between adsorption and desorption of the mobile pore fluids. For computational purposes, a Freundlich or Langmuir non-linear sorption isotherms may be followed depending on the specific surface area of the complex pore geometry. Thus, the computational fluid dynamics associated with the storage, release, and diffusion of fluids within low-permeability rock-matrix, high-permeability fracture and over fracture walls remains challenging.

A. *Mathematical Conceptualization*

The mathematical conceptualization of flow and transport processes of interest at an individual pore scale is available and leads to Navier-Stokes equation. However it is not possible to characterize completely the extreme heterogeneities of the fracture-matrix coupled system. Even if it were, in most practical applications the transport domain is much too great for computer simulation on the basis of a solution using the Navier-Stokes equation. Therefore, most models provide the description of solute transport at a macroscopic scale. The Advective Dispersive Equation (ADE) remains the foundation on which most analyses of solute transport in porous media have been used. However, for spatial scales within which pronounced variations in pore water velocity exist, the traditional ADE may not be a valid description. Hence, in a fracture-matrix coupled system, where a distinct heterogeneity is seen between high permeability fracture and low permeability rock matrix, an improved concept is needed to represent the system well and such a concept is a well known dual porosity concept and used for the analyses of solute transport in a coupled fracture-matrix system. Since fractures have a multi-scale variability that cannot be fully described even by dual porosity concept, and since, large-scale (kilometer) long-term predictions are needed, whereas experiments are performed at the meter and day scale, numerical modeling of its transport behavior is an important issue.

From the analysis of breakthrough curves obtained from the numerical simulations, it has been found that many of the breakthrough curves have significant tails. Tailing is caused by borehole storage, dispersion, matrix and molecular diffusion, transport in different channels, and desorption. From the literature review, it is now well understood that fractured aquifers are highly complex in nature as they contain extreme heterogeneities in the form of high permeability fracture and low permeability rock matrix. Groundwater contaminant transport through these fractures exhibits strongly varying solute velocity fields caused by matrix diffusion. Thus the center of mass of the contaminant front does not travel with the average fluid velocity and hence the spread around the center of mass of the solute cannot be described by traditional Fickian process, which forms a reasonable approximation only under high degree of homogeneity in the permeability field. Also, field and laboratory analyses demonstrate that dispersivity derived from ADE is not constant but is dependent on the time and/or length scale of measurement characterized by early breakthrough and elongated tails. Such time-dependent dispersion is referred to a “non-Fickian” transport resulting from heterogeneities at all scales. Taking this argument into account, attempts have already been made that considers detailed analyses of ADE which does not provide adequate representations of contaminant migration. Much attention has been paid, for understanding the scale dependent behavior of dispersivity resulting from effective macro-dispersion of solutes in porous media affected by hydraulic conductivity variations. However, a few studies have been attempted for analyzing this behavior in a fracture-matrix coupled system. Also, the focus of several studies in fractured rocks is to understand and to predict the effective solute velocity and macro-dispersion in fracture-rock system.

While most of the current attention of the research community is focused on modeling flow and transport in fractured porous media, there is still considerable interest in flow and transport in individual fractures. While this may appear to be a case of researchers avoiding the hard problem and gravitating to the easy problem, there are justifiable reasons to consider a single fracture. First, a comprehensive and fundamental understanding of flow and transport in a single fracture is vital in developing realistic, yet tractable, models of fractured porous media as a whole. The results of the analysis of flow and transport in a fracture are useful in determining which physiochemical processes should be included, and which can be ignored, under certain situations. Second, analysis of flow and transport in a single fracture can lead to model equations that can be used in fracture network models. Third, the insight gained through a careful study of a single fracture is useful in analyzing the results of numerical simulations of fractured porous media and interpreting the data from field experiments. Finally, individual fracture-matrix systems can be constructed in the laboratory. As a result, theoretical models can be verified.

B. Physical System and Numerical Complexities

An understanding of fluid flow and solute transport in hard rocks – at the very basic level – needs a clear understanding on whether the concerned rock formation can be treated as an Equivalent Continuum Model (similar to a porous medium) or as Dual Porosity/permeability in the absence of considering a rock as a complex network of fractures. If the rock is well exposed to physical and chemical weathering, and if it is relatively nearer to the surface, then, the rock can be idealized to have a higher fracture density, and a higher fracture spacing, and eventually, the system can be treated as an Equivalent Continuum Model, where the value of hydraulic conductivity for fracture and rock-matrix are averaged suitably (called as effective or equivalent hydraulic conductivity), and this mean value is a single value as against the dual values followed in dual porosity/permeability model [18]. [19] have numerically shown when a fractured formation can be considered to be an equivalent continuum or a dual-porosity system based on variation of exponent of mean fluid velocity with asymptotic dispersion coefficient. Further, [20] have numerically shown that the fluid velocity in the coupling term, which decides the residence time of solutes within the fracture, and in turn, decides the intensity of fracture-matrix coupling plays a significant role in deciding the fluid mass transfer between fracture and rock-matrix. It can be noted that this term on the effect of fluid velocity is currently not considered in the conventional fluid mass transfer term. On the other hand, modeling a fractured rock as a dual porosity/permeability system needs to ensure the connectivity of fractures towards the production well. It can be noted that such connectivity requires hydraulic stimulation, which needs heavy investment. Thus, the idealization of parallel plate fractures, as followed by a group of scientists who work on hard rock aquifers, though seems simple to simulate numerically, it is apparently neither easy nor straight-forward from actual field perspective.

Regarding fluid flow through a fractured formation application of Cubic Law to describe the fluid flow rate is more appropriate as against conventional Darcy’s Law. It can be noted that - in Darcy’s law – which is meant for a porous system, the porosity cannot be equal to 100%, in which case, the Darcy flux and the seepage velocity becomes equal, while - in Cubic law – which is meant for flow through fractures, can have 100% porosity – which is similar to flow through pipes (and hence, the very concept of Cubic Law has been deduced from Navier-Stokes Equation). It can also be noted that the discharge though classical porous medium is directly proportional to square of the mean grain size diameter, while the discharge through the fractured formation is directly proportional to the cube of the fracture aperture (or void). Thus, it should be clearly noted that applying conventional Darcy's law by assuming an effective or equivalent hydraulic conductivity to compute the discharge may be significantly different from that computed by Cubic law.

Conventional solute transport equation used to describe the advective, diffusive and dispersive processes has coefficients (for example, velocity and hydrodynamic dispersion coefficient) which are constant with respect to space and time. In other words, the physical system is supposed to follow a Fickian behavior of solute transport. However, in hard rocks, due to the marked heterogeneity between high-permeability fracture and low-permeability rock matrix, and particularly, in a dual porosity system, the physical system follows a Non-Fickian behavior whereby the coefficients become functions of space and time [21]. Hence, the concept of scale-dependency becomes very critical [22]. Although spatial moment analysis deduces the variation of velocity, it remains a question, whether how far the predicted results at the scale of a single fracture can be up-scaled with more reliability. For example, there is no concept of mixing or dispersion of solutes at the fracture intersection – at the scale of a single fracture, while the same is inevitable at the field scale. Hence, the study at the scale of a single fracture provides a further scope on studies pertaining to up-scaling of result from the scale of a single fracture to a complex network of fractures, and eventually, the number of additional parameters that would come into picture, during this up-scaling may be deduced.

The concept of fracture-skin, which is generally not included in a coupled fracture-matrix system, plays a very crucial role in deciding the depth of penetration of contaminants, and thus plays a very crucial role at the scale of a single fracture [23], [24]. For example, there is always a debate on - whether the radioactive wastes (when the nuclear wastes leaches out of the repository resulting from accumulated small scale seismic activities, and migrates through the high permeability fractures) – penetrate the entire depth of fracture spacing (or the thickness of rock-matrix) as described by the partial differential equation for rock-matrix, or not. In most of the cases, it can be presumed that depth of penetration of wastes or contaminants from the fractures into the rock-matrix is not complete as its associated fracture spacing – at such greater depths – may be either significant or very high. Under such circumstances, the assumption of uniform diffusion of solutes as described by the rock-matrix equation needs to be relooked. On the other hand, assumption of very small fracture spacing (for numerical simplicity) may lead to the concept of "Back-Diffusion" and eventually, would lead to boundary effects.

The role of sorption in the case of transport through a fractured formation plays a very crucial role at the scale of a single fracture [25]-[31]. When the transport of contaminants is studied in the context of groundwater supply, then the fluid flow along the fracture may not be having significant residence time within the fracture, and eventually, the role of non-linear sorption may not be so significant. On the other hand, when the same transport of contaminants or solutes is studied in the context of nuclear waste disposal, then the role of non-linear sorption becomes very crucial. This is because the number of available sorption sites within the rock-matrix (which keeps on increasing as we increase the fracture spacing) is higher by several orders of magnitude, despite a limited number of sorption sites on the fracture walls. It can be noted that all the nuclear wastes that may leach out after its burial should not find its way to the biosphere, and it is generally expected that the rock-matrix would act as a natural barrier (as against an engineered barrier), and eventually, it would try to reduce the intensity of radioactive waste radiation towards the biosphere.

The role of radioactive decay obviously proves to be very crucial as well as detrimental at the scale of a single fracture [31]. The numerical results suggest that the radioactive wastes that have been leached out of the nuclear waste repository and which find its way to the biosphere along the high permeability fracture gets decayed to nothing at a relatively shorter period (less than a few years). It should be noted here that – for a significant fracture length - when the radioactive wastes gets vanished due to its decaying nature, the mathematical modeling needs an utmost care – as the total mass is no more conserved – when the contaminants are in the form of nuclear wastes. And subsequently any forecasting in the absence of ensuring mass conservation within the fracture needs a careful observation.

The conventional approach of considering the longitudinal dispersivity value to be 10% of the total aquifer length – as suggested by Gelhar - may not be valid – when there is transport of solutes in a coupled fracture-matrix system. The longitudinal dispersivity is scale-dependent and it is significantly higher in a hard rock formation due to the inherent heterogeneity.

The conventional assumption of parallel plate fractures may not be always valid - as – in reality – we may find fractures to have rough corrugated surfaces. Attempts have been made to consider the solute transport along the sinusoidal fracture surfaces [32]-[37], and triangular fracture surfaces [18] at the scale of a single fracture. Under such circumstances, considering conventional solute transport equations need to be relooked. Because, (1) when the fluid flow rate is significant along the fracture, then, there is a possibility of vortex formation along the periphery of sinusoidal walls; and (2) when the fluid flow rate is insignificant, then, the mass transfer rate may not be the same at every point along the fracture. For these reasons, a modified coupling term needs to be deduced which will consider a spatially varying mass transfer coefficient as against the conventional constant mass transfer coefficient.

In mathematical modeling, the fluid flow through hard rock is conceived as the fluid flow through a set of parallel fractures. However, in field conditions, there is a possibility that the aperture size at some point may become less than 10 microns, where the flow cannot be expected to be driven either by pressure or by gravity, but by capillary pressure. Thus, the equations used to describe the solute transport and the actual fluid flow processes may be totally different, and one has to ensure that the fracture aperture is quite significant. On the other hand, if the size of the fracture aperture is too large (like more than 1000 microns), then the fluid flow within the fracture essentially gets divided into two regimes. The first regime around the centre of the fracture axis is characterized by the relatively dominant advective flow nature, while the second regime (which is away from the fracture axis and forms towards the fracture-matrix interface) is characterized by the diffusive flow nature. Under such circumstances, the mass transfer coefficient described by the conventional coupling term may not be a constant and it needs to be modified.

When the fracture surfaces are considered to be parallel to start with (i.e., under initial conditions when time = 0), and if the fracture aperture is allowed to vary resulting from precipitation and dissolution, thermo-elasticity and/or poro-elasticity, the mean velocity at every point will change in order to maintain the constant assumed discharge [38]-[42]. However, one has to carefully follow this assumption, because at any given time, if any one of the point along the fracture has a pressure higher than that of the inlet pressure, then, the system behavior would deviate from its modeling assumptions. Hence, the pressure within the fracture should not be allowed to exceed the inlet pressure at any point of time.

Assuming a uniform diffusion of solutes within the low-permeability rock-matrix – described by a constant diffusion coefficient – may not always be correct. Depending on the type of wastes, the region within the rock-matrix around the fracture-matrix interface may have differing porosities – as against the assumed constant porosity for the entire rock-matrix and/or fracture-skin. These differing porosities may significantly affect the rates of diffusion within the rock-matrix. Thus, under such circumstances, a spatially and/or temporally varying diffusion coefficient may provide better results.

When the radioactive wastes such as Cesium (137), Plutonium (239) and Selenium do not migrate as free solutes, but rather as solutes sorbed to colloids, the concept of Colloid-Facilitated transport plays a crucial role. In fact, colloid-facilitated transport in a fracture-matrix coupled system tries to bring back anomalies. In other words, presence of colloids makes the solutes to arrive early; reduces the peak mitigation of concentration; and, reduces the tailing effect on the descending limb of concentration profile with a steep gradient. Thus, the typical features of a coupled fracture-matrix system such as delayed arrival of solutes; peak mitigation of concentration; and the tailing of curves may not be seen when the transport is co-facilitated by the colloids [43], [44].

The presence of colloids within the fracture may also lead to an enhanced dispersion (in addition to the enhanced dispersion resulting from fracture rock-matrix coupling) as colloids try to remain in the mobile phase – relatively – for a longer period than that of solutes. Under such circumstances, delineating the enhanced dispersion resulting from different origins may not be straight forward, and eventually, the interpretation from spatial second moments needs a careful observation.

V. CONCLUSIONS

This paper has provided a review on few aspects fluid dynamics of a fractured reservoir at the scale of a single fracture. This paper has made an attempt to project how the mathematical conceptualization for a fractured reservoir deviates significantly from that of a classical porous medium. In addition, the numerical complexities aspects of computational fluid dynamics arising from the distinct heterogeneities between high permeability fracture and its associated low-permeability rock-matrix has been discussed. In essence, an attempt has been made to project that the fluid dynamics in a fractured reservoir is significantly different from that observed in a classical porous medium, and eventually, extreme care needs to be exercised when the porous medium concepts are applied to a fractured reservoir.

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Dr. G Suresh Kumar started working on “Fluid Flow through Hard-Rocks” right from his Masters Degree at Guindy Engineering College, Center for Water Resources, Anna University. Later he joined IISc (Bangalore) to pursue his doctoral program on “Numerical Modeling of Reactive Solute Transport in Hard-Rocks”. Then, he moved to University of North Dakota (USA) to pursue his post-doctoral program on “Geothermal Energy Extraction from Fractured Reservoirs”. Later, he moved to Queen’s University (Canada) to work on “Migration of Nuclear Wastes through Hard Rocks“. Later, he was working as Assistant Professor for a year at IIT-Guwahati before joining at IIT-Madras. He is currently working as Associate Professor at IIT-Madras in the Department of Ocean Engineering. His research interest revolves around “Numerical Modeling of Subsurface Fluid Flow”. He has authored 30 International Journal papers and has received 2 Best Paper Awards to his credit. He is currently guiding 7 doctoral students along with MS and M Tech students.