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The Multiphase Flow Analysis for Fluid in Porous Rocks

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Abstract

The flow of multiphase to porous sources is a complex matter with a long and rich history in the field of fluid mechanics. This is a topic that has important technological applications, especially in the construction of oil on petroleum reservoirs and so on. The flow of single-phase fluid in a pore area is best illustrated by Darcy's law. In the petroleum industry and in other technological applications, transportation is modeled by submitting a multiphase generalization of Darcy law. In these connections, different pressures are defined in each phase which includes differences known as capillary pressures, determined by interface inconsistencies, micro pore geometry and surface chemistry of the solid surface. With flow rates, relative access is defined which associates the flow rate of each fluid volume with its pressure gradient. In the present paper, there are discoveries and analyzes about the equation for the distribution of liquid flow in perforated rocks and other important results have been established. Permeability is the activity of a type of rock that varies in pressure, temperature, etc., and does not depend on the liquid. The effect of liquid on the flow rate is calculated according to the viscosity term. The number of entrances to a given stone depends on the size of the holes in the rock and the degree of connection of the empty space. Pressure pulses listen to the distribution equation and not the wave equation. Then they move at a slower pace than they do at a steady pace. The results shown in this paper are very useful in the science of the world and in the petroleum industry.

Keywords: Darcy Act, Diffusion equation, Multiphase Flow, Hollow Stone.

1. Introduction

To discuss the flow of fluid in porous sources, we first discuss groundwater. Groundwater systems contain many of the world's fresh water, which provides much of the water needed for human society and ecosystems. Underground water is usually from hundreds to thousands of years, making it the most independent source of water in the caprice of the season associated with many surface water sources.

Due to the world's largest source of drinking water, protection of this source is essential to ensure widespread access to reliable sources of clean water. Conditions of groundwater pollution are common, and many can be identified as serious risks to public health. But from long-term habitats it often extends to groundwater pollution and pollution may be involved with long-term harmful impacts on polluted resources. Non-aqueous phase liquids (NAPLs) represent a contamination phase where existing remedial strategies are particularly prevalent. NAPL pollution systems are common, ranging from improper disposal of industrial solvents, leakage of underground storage tanks containing petroleum products, disposal and byproducts of refining and firing of coal gas [1], [7], [8]. NAPLs do not mix in water, and many melt in small amounts. Once NAPLs are introduced into the pollution system it can last for decades or even centuries [12], [13]. The development of useful corrective strategies for these systems has not been very successful, and the standard mathematical methods used to provide flow behavior of these systems are subject to many potential problems, which greatly reduce their predictive capacity [9], [10]. The modeling methods used are not particularly effective in many fluid phases, and more accurate mathematical explanations are needed to analyze the risks involved in pollution, improve basic understanding of system behavior, and develop corrective strategies related to these systems.

Consideration of perforated media within a multi-dimensional framework emerges an emerging concept that exploits a mature perception that operates on a small scale in length as a means of interpreting large-scale schemes. Many body systems can be associated with a series of height measurements; each is associated with a specific mathematical formula that describes the behavior of the system on that scale. Multi-scaled structures provide relationships between these different meanings, which provide a series of mathematical formations.

When this is used in small media the method can be used to bind large thermodynamic forms and storage figures to those operating in the port scale, otherwise known as small scale. This is useful if the macroscopic closure relationship is unreliable or incomplete; minor closure relationships are often better known. Microscopic simulations can therefore be used to provide information on extreme behavior, judges to facilitate speculation, and to produce appropriate relationships for greater closure. These studies rely heavily on computational methods to provide real-world solutions for microscopic analysis of porous medium flow. Computer analysis provides opportunities to incorporate greater and more realistic data for small analytical behavior in the analysis of larger models.

In Germany and many other countries more than half of the population depends on groundwater for drinking water [4]. Problems with groundwater quality stem from landfills, leaking tanks and accidental spills of industrial equipment. Removing these substances from the underground space is very complex and difficult, if possible [6]. In order to design effective remedies it is important to understand the regulatory mechanisms of flow and transport in porous sources. Mathematical modeling is one of the most important ways to help get targeted. Including detailed data on physics and geometry in mathematical models requires the use of numerical algorithms and compatible computers.

Now, these objects contain flexible components that are transported in the air phase. When the supply of LNAPL stops, a certain amount of it remains immovable in the soil at the base of the residue. The density of NAPL (DNAPL) is heavier than water and its flow behavior in a waterless area is the same. But because of its great congestion it goes down again with full sinners. But due to the effects of capillary heterogeneities in the soil it plays an important role in the flow of multiphase. The regions of the small holes are not filled with liquid until the accumulation of vital fluids accumulates. The dimensions of these regions may vary from centimeters leading to the extraordinary spread of NAPL on the sides to meters in the construction of DNAPL pools. NAPLs provide a long-term problem with groundwater quality. Initial entry may occur in hours or days while the resolution process may occur over the years. The low concentration of NAPL in a series of 10 makes water unsuitable for drinking. With the large number of procedures listed it is evident that the mathematical modeling of the correction processes can be very difficult. In the simplest example of an unchanging two-phase flow, the mathematical model is related to two separate non-linear calculated segments based on time. But the detailed geometry of the medium porous is impossible to determine its complex structure is effectively known for several parameters in mathematical calculations. It is a basic problem for all medium flow models to get these parameters. But due to the heterogeneity of the porous medium at different lengths these functional parameters depend on the scale. Different ways have been found to address this problem. Here we have talked about stochastic modeling [5], upscaling [2] and parameter identification [11] .We have so far focused on the problems of groundwater processing as our motive for the consideration of excess fluid flow in porous sources. In addition there are other important applications of these types such as oil tank exploitation and safety analysis of underground waste storage facilities. The latter system is often complicated by the presence of cracks in the solid rock [3].

With the flow of porous media, Darcy's equation has been used. Darcy's calculations are generally based on the principle of linear regression between speed and pressure gradient in narrow media. The line element is expressed as porosity and represents the flow resistance in solid media. The flow process in pore media is governed by certain visual conditions such as viscous forces and forces arising from the solidity of the surface between solids and liquids, but also more tensions between different layers of liquid. The flow process is involved in a goal developed by the use of the equation, but it takes more effort to simulate resolving the force equation than using Darcy's equation. For this reason Darcy's equation is widely used to mimic the flow of fluid through pore media.

2. Governing Equations

The basic law governing the flow of fluids through porous media is Darcy’s law, which was formulated by the Henry Darcy in 1856 on the basis of his experiments on vertical water filtration through sand beds. The detailed derivation related to diffusion was given by R. W Zimmerman in 2002 [14]. Darcy found that his data could be described by

$$Q = \frac{C\,A\,\Delta(P - \rho g z)}{L} \tag{1}$$

Where

P = pressure [Pa]

ρ = density [kg/m^3]

g = gravitational acceleration [m/s^2]

z = vertical coordinate (measured downwards) [m]

L = length of sample [m]

Q = volumetric flow rate [m^3/s]

C = constant of proportionality [$m^2/Pa\ s$]

A = cross-sectional area of sample [m^2]

Any consistent set of units can be used in Darcy’s law, such as SI units, C.G.S. units etc. But in the oil industry it is common to use “oilfield units”, that are inconsistent. The Darcy’s law is mathematically same as other linear transport laws, such as Ohm’s law for electrical conduction, Fick’s law for solute diffusion and Fourier’s law for heat conduction. By the fluid mechanics we know that Bernoulli’s equation contains the terms:

$$\frac{P}{\rho} - g\,z + \frac{V^2}{2} = \frac{1}{\rho}\left(P - \rho\,g\,z + \rho\frac{v^2}{2}\right) \tag{2}$$

where P/ρ is related to the enthalpy per unit mass, $g\,z$ is the gravitational energy per unit mass, $v^2/2$ is the kinetic energy per unit mass. But the fluid velocities in a reservoir are small then the third term can be neglected. And we see that the term $(P - \rho g\, z)$ represents a term of energy type. That seems reasonable that the fluid can flow from regions of higher to lower energy so, the driving force for flow must be the gradient of $(P - \rho g\, z)$. But due to Darcy's analysis, it has been found that all other factors being equal, Q is inversely proportional to the fluid viscosity. It is therefore suitable to factor out μ, and put $C = k/\mu$, where k is known as the permeability. On taking the volumetric flow per unit area, $q = Q/A$. Now the Darcy's law can be written as:

$$q = \frac{Q}{A} = \frac{k}{\mu}\frac{\Delta(P - \rho g z)}{L} \tag{3}$$

where the flux q has the dimensions of [m/s]. It is perhaps easier to say of these units as [m^3/m^2s].

For transient processes in which the flux varies from the point to point, we can write a differential form of Darcy's law. In the vertical direction, this equation can be written as:

$$q_v = \frac{Q}{A} = -\frac{k}{\mu}\frac{d(P - \rho g z)}{dz} \tag{4}$$

where the suffix v is taken for vertical flow. The minus sign is taken since the fluid flows in the direction from higher potential to lower potential. The differential form of Darcy's law for one-dimensional horizontal flow can be

$$q_h = \frac{Q}{A} = -\frac{k}{\mu}\frac{d(P - \rho g z)}{dx} = -\frac{k}{\mu}\frac{dP}{dz} \tag{5}$$

where the suffix v is taken for vertical flow. In most rocks the permeability k_h in the horizontal plane is different than the vertical permeability, k_v ; in most of the cases, $k_h > k_v$. The permeabilities in any two orthogonal directions within the horizontal plane have the difference. So, in this course we shall generally take: $k_h = k_v$. The permeability is the function of rock type, that varies with stress, temperature etc., but it does not depend on the fluid; the effect of the fluid on the flow rate is accounted for by the term of viscosity in the above equations. The permeability has units of m^2, but in mathematical use it is conventional to use "Darcy" units, defined as:

$$1\,Darcy = 0.987 \times 10^{-12}\ \mathrm{m}^2 \approx 10^{-12}\ m^2$$

The Darcy unit is defined such that a rock having a permeability of 1 *Darcy* would transmit 1 c.c. of water with viscosity 1 *cP per second*, through a region of 1 sq. cm. cross-sectional area, if the pressure drop along the direction of flow were 1 *atm per cm.* Many soils and sands that mathematicians must deal with have permeabilities on the order of a few *Darcies*. The original purpose of the "*Darcy*" definition was thus to avoid the need for using small prefixes such as 10^{-12} etc. But a Darcy is nearly a round number in SI units, so conversion between the two is easy. The numerical value of k for a given rock depends on the size of the pores in the rock, d as well as on the degree of interconnectivity of the void space. So that

$$k \approx d^2/1000$$

where d denotes the diameter of the pores. The permeabilities of different types of rocks and soils vary over many orders of magnitude. However, the permeabilities of petroleum reservoir rocks tend to be in the range of 0.001-1.0 *Darcies*. So it is convenient to refer the permeability of reservoir rocks in units of "*milliDarcies*" (*mD*), which equal 0.001 *Darcies*. In some reservoirs, the permeability is due mainly to an interconnected network of fractures. The permeabilities of fractured rocks tend to be in the range 1 *mD* to 10 *Darcies*. In a fractured reservoir, the reservoir scale permeability is not closely related to the core scale permeability that anyone can measure it.

If the fluid is in static equilibrium then $q = 0$, so the differential equation will be

$$\frac{d(P - \rho g z)}{dx} = 0 \Rightarrow P - \rho g z = \text{constant} \tag{6}$$

If we take $z = 0$ i.e., at sea level, where the fluid pressure is equal to the atmospheric pressure, then we have

$$P_s = P_a + \rho\, g\, z \tag{7}$$

where P_s, P_a represent the static pressure and atmospheric pressure respectively. But we always measure the pressure above the atmospheric pressure, so we can neglect the term P_a in the above equation (7). We can see by comparing equation (7) with equation (4) that only the pressure above and beyond the static pressure given by equation (2) plays a role in driving the flow. So the term $\rho g z$ is useless, as it only contributes to the static pressure and but does not contribute to the driving force for the flow. Then after removing the term, the equation for correct pressure will be

$$P_c = P - \rho g z \tag{8}$$

Now the Darcy's law in the terms of corrected pressure for the horizontal flow can be written as:

$$q = \frac{Q}{A} = -\frac{k}{\mu}\frac{dP_c}{dx} \tag{9}$$

Instead of using sea level i.e., $z = 0$, we can take $z=z_0$ as a datum i.e., the amounts of initial oil in place lie above and below $z=z_o$. So we get

$$P_c = P - \rho\, g\, (z - z_o) \tag{10}$$

The data rate selection is not visible, in the sense that it provides a constant time for adjusted pressure, it does not affect pressure. The pressure Pc described in equation (10) can be interpreted as the pressure of the analytical fluid at $z = z_o$ depth which will be in the equilibrium and the liquid and present at the actual pressure at the z depth. Darcy's law should be a macroscopic law aimed at targeting regions larger than the size of a single hole. Now we can talk about entering a place in the water reservoir, we will not be referring to the entrance to a limited area of mathematics as a given point can be a grain of sand and not a hole. Accessibility property is actually defined as a patchwork area, not a single patch. Accessibility is therefore a descriptive element of measurement in a particular area around a point (x, y, z). Now the region should be large enough to cover a large number of pores. The pressure P used in Darcy's law is actually an intermediate pressure taken from a small area of space.

When we refer to stress at a certain point in a lake, we do not distinguish between two adjacent points such as these. Therefore, the whole region shown in the picture will be represented by the central pressure taken from the displayed circle area, i.e. known as the Representative Elementary Volume (REV). Similarly, stone penetration is defined by the REV length measurement. Regarding REV size, we can say that it should be at least one order size larger than the hole size.

Darcy's law itself does not provide sufficient information for time-dependent solutions i.e., temporary problems involving groundwater flow. So in order to get the perfect governing body that works on these problems, we will first have to find the mathematical expression of the weight loss goal. Maintenance of large figures means the balance between the rate of weight change by the unauthorized volume and the entry of weight in the boundary area. In the combined form, this can be expressed as follows:

$$\frac{\partial}{\partial t}\iiint \rho\, \phi\, dV + \iint \rho\, \bar{v}.\bar{n}\, dS = \iiint q\, dV \tag{11}$$

In this equation the double and triple integrals are taken over surface and volume respectively and $\bar{v}, \bar{n}, \rho, q$ and ϕ represent the velocity vector, unit normal vector, fluid density, external mass flow rate and porosity respectively. The right hand side term of the equation (11) can be changed into a volume integral form by the using the Gauss' divergence theorem as:

$$\iint \rho\, \bar{v}.\bar{n}\; dS = \iiint \nabla.(\rho\, \bar{v})\; dV \tag{12}$$

So, for a fixed control volume, the integral form of the conservation law will be

$$\iiint \left[\frac{\partial(\rho\, \phi)}{\partial t} + \nabla.(\rho\, \bar{v}) - q\right] dV \tag{13}$$

Now the differential form the conservation equation for mass can be written in coordinate invariant form as:

$$\frac{\partial(\rho\, \phi)}{\partial t} + \nabla.(\rho\, \bar{v}) = q \tag{14}$$

For the multiphase flow, it is necessary to account for the saturation of each phase. So that the equation (14) within each phase α can be written as:

$$\frac{\partial(\rho_\alpha\, S_\alpha \phi)}{\partial t} + \nabla.(\rho_\alpha\, \bar{v}_\alpha) = q_\alpha \tag{15}$$

3. Diffusion Equation in Cartesian Coordinates

The transient flow of a fluid through a porous medium is governed by a certain type of partial differential equation known as a diffusion equation. The detailed derivation and discussion related to diffusion was given by R. W. Zimmerman in 2002 [14] *i.e.,* discussed in this paper. So to derive the equation, we combine Darcy's law with the law of mass conservation and an equation that describes the process for which the fluid is stored inside a porous rock. Now using the differentiation for the product function $(\rho\, \phi)$, we get

$$\begin{aligned} D(\rho\, \phi) &= \rho\, D\phi + \phi\, D\rho, D \equiv \frac{d}{dt} \\ &= \rho \frac{d\phi}{dP}\frac{dP}{dt} + \phi \frac{d\rho}{dP}\frac{dP}{dt} \\ &= \phi\left[\left(\frac{1}{\phi}\frac{d\phi}{dP}\right)\frac{dP}{dt} + \rho\left(\frac{1}{\rho}\frac{d\rho}{dP}\right)\frac{dP}{dt}\right] \end{aligned} \tag{16}$$

$$D(\rho\, \phi) = \rho\, \phi\, (c_R + c_f)\, D(P) \tag{17}$$

where $c_R,\ c_f$ are the compressibility of the rock and the fluid respectively.

The equation for mass conservation for the fluid flow is taken as:

$$-\frac{d(\rho\, q)}{dx} = \frac{d(\rho\, \phi)}{dt} \tag{18}$$

By using the Darcy's law, we have

$$-\frac{d(\rho\, q)}{dx} = -\frac{d}{dx}\left[-\frac{\rho k}{\mu}\frac{dP}{dx}\right]$$

$$-\frac{d(\rho\, q)}{dx} = \frac{k}{\mu}\left[\rho \frac{d^2 P}{dx^2} + \frac{d\rho}{dx}\frac{dP}{dx}\right]$$

$$-\frac{d(\rho\, q)}{dx} = \frac{k}{\mu}\left[\rho \frac{d^2 P}{dx^2} + \frac{d\rho}{dP}\frac{dP}{dx}\frac{dP}{dx}\right]$$

$$-\frac{d(\rho\, q)}{dx} = \frac{k\rho}{\mu}\left[\frac{d^2 P}{dx^2} + \frac{1}{\rho}\frac{d\rho}{dP}\left(\frac{dP}{dx}\right)^2\right]$$

$$-\frac{d(\rho\, q)}{dx} = \frac{k\rho}{\mu}\left[\frac{d^2 P}{dx^2} + c_f\left(\frac{dP}{dx}\right)^2\right] \qquad (19)$$

From the equations (17) and (19), we get

$$\frac{d^2 P}{dx^2} + c_f\left(\frac{dP}{dx}\right)^2 = \frac{1}{K}\rho\, \phi\, (c_R + c_f)\, D(P) \qquad (20)$$

But we know that,

$$\frac{d^2 P}{dx^2} \gg c_f\left(\frac{dP}{dx}\right)^2$$

On neglecting the term $c_f\left(\frac{dP}{dx}\right)^2$ $, i.e.$

$$c_f\left(\frac{dP}{dx}\right)^2 \approx c_f\left[\frac{\mu\, Q}{2\,\pi\, k\, H\, R}\right]^2 \qquad (21)$$

$$\frac{d^2 P}{dx^2} \approx \frac{\mu\, Q}{2\,\pi\, k\, H\, R^2} \qquad (22)$$

So we can neglect the nonlinear term in equation (20), we get the diffusion equation as given

$$\frac{dP}{dt} = \frac{K}{\phi\, \mu\, (c_\phi + c_f)}\frac{d^2P}{dx^2} \qquad (23)$$

where $(c_\phi + c_f) = c$ is the total compressibility.

The parameter which governs the rate at which fluid pressure diffuses through the rock is the hydraulic diffusivity D_H, that is defined by

$$D_H = \frac{k}{\phi\, \mu\, (c_\phi + c_f)} \qquad (24)$$

The distance d at which a pressure disturbance will travel during an elapsed time t is given as

$$d = \sqrt{4\, D_H t} \qquad (25)$$

For the multi-phase flow if we have assume that the pores of the rock are filled with two components, oil and water, and often also contain some hydrocarbons in the gaseous phase. So we have to find the governing flow equations for an oil and water system, in the general form. From the rock properties module that Darcy's law can be generalized for two-phase flow by including a relative permeability factor for each phase, we have

$$q_w = \frac{-kk_{rw}}{\mu_w}\frac{dP_w}{dx} \tag{26}$$

$$q_o = \frac{-kk_{ro}}{\mu_o}\frac{dP_o}{dx} \tag{27}$$

where the subscripts w and o are used for oil and water respectively. The two relative permeability functions are supposed to be known functions of the phase saturations. For the oil-water system, the two saturations are necessarily related to each other by the relationship

$$S_w + S_o = 1 \tag{28}$$

The pressures in the two phases at every point in the reservoir must be different. If the reservoir is oil-wet then the two pressures will be given by

$$P_o - P_w = P_c\, S_o \tag{29}$$

where the capillary pressure P_c is given by the rock-dependent function of oil saturation.

But the volume of the oil in a given region is equal to the total pore volume multiplied by the oil saturation then by the equations of the conservation of mass for the two phases can be written by inserting a saturation factor in the storage term as given

$$-\frac{d(\rho_0 q_0)}{dx} = \frac{d(\phi\rho_0 S_0)}{dt} \tag{30}$$

$$-\frac{d(\rho_w w)}{dx} = \frac{d(\phi\rho_w S_w)}{dt} \tag{31}$$

The densities of the two phases are related to their respective phase pressures with the equation of state as given by

$$\rho_0 = \rho_0(P_0) \tag{32}$$

$$\rho_w = \rho_w(P_w) \tag{33}$$

where the temperature are taken as constant.

Lastly, the porosity must be the function of the phase pressures Po and Pw. The above two pressures independently affect the porosity. Now, the capillary pressure P_c is generally small so that

$$Po \approx Pw$$

From which we can use the pressure-porosity relationship that would be obtained under single-phase conditions, *i.e.,*

$$\phi = \phi\,(P_0) \tag{34}$$

If the fluid is taken as slightly compressible or if the pressure variations are small then the equations of state are written as

$$\rho(P_o) = \rho_{0i}[1 + c_o\,(P_o - P_{oi}\,)] \tag{35}$$

where the subscript "i" is used for the initial state, and the compressibility c_o is taken as a constant.

4. Conclusions

The permeability is a function of rock type that varies with stress, temperature etc., and does not depend on the fluid. The effect of the fluid on the flow rate is accounted for by the term of viscosity. The numerical value of k for a given rock depends on the diameter of the pores in the rock "d" as well as on the degree of interconnectivity of the void space. The parameter that governs the rate at which fluid pressure diffuses through a rock mass is the hydraulic diffusivity which is defined by

$$D_H = \frac{k}{\phi\,\mu\,c}$$

The distance *d* at which a pressure disturbance will travel during an elapsed time *t* is given as

$$d = \sqrt{4\,D_H t}$$

The time required for a pressure disturbance to travel a distance *d* is found by

$$t = \frac{\phi\,\mu\,c\,d^2}{4k}$$

The pressure pulses obey a diffusion equation not a wave equation. So, they travel at a speed that continually decreases with time rather than travelling at a constant speed.

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