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Fluid Motion in Radial Coordinates with respect to Porous System

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Abstract

The flow of multiphase to porous sources is a matter of major problems with a very wide history in the field of fluid mechanics. This is a topic of important technological applications, most likely to find oil in petroleum reservoirs and more. The flow of single-phase fluid in a pore area is analyzed by Darcy's law. In the petroleum industry and in other applications, transportation is modeled by submitting a multiphase generalization of Darcy's law. In this relationship, the different pressures are defined across all different holding phases, referred to as capillary pressure and determined by micro pore geometry, friction between the surface and the surface dense chemical surface. With flow rates, the relative access is defined which corresponds to the flow rate of the entire liquid and its pressure gradient. In the present paper, there is the discovery and analysis of the distribution equation in radial coordinates for the flow of fluid in pore rocks and some useful results have been established. Permeability is the activity of a type of rock that varies in temperature, pressure, etc., and is independent of the liquid. The effect of liquid on the flow rate is calculated by viscosity. The number of entrances to a given stone varies with the size of the holes in the rock and the degree of connection of the empty space. Pressure pulses satisfy the distribution rate instead of the number of waves. Then they move at a slower pace than they do at a steady pace. The results shown in the paper are very useful in the science of the world, in the petroleum industry and so on.

Keywords: Darcy's Law, Diffusion equation, Porous rock, Radial links.

1. Introduction

The concept of a hollow media within a multi-scale framework is an idea that takes advantage of a mature perception mode that operates on a low-level scale as a means of interpreting large scale scaling systems. Several body systems can be linked to a series of height measurements; everyone is associated with a certain mathematical formula that describes behavior on that scale. The functions of the multi-scale framework provide links between these various definitions that provide mathematical sequence.

If those are used in microscopic media the method can be used to combine large thermo dynamical forms with the savings figures of those operating on a small scale, otherwise known as a small scale. This is useful when macroscopic closure relationships are incomplete or unreliable; microscopic closure relationships are better known. Microscopic analysis can be used to provide information on macroscopic behavior, judges facilitating thoughts and building appropriate macroscopic relationships. This analysis relies heavily on computational methods to provide real-world solutions for microscopic analysis of porous medium flow. Computer analysis provides opportunities to incorporate larger and more realistic interpretations of small analytical behavior into larger model analysis.

With the flow of porous media, Darcy's equation has been used. Darcy's calculation is usually based on the principle of linear regression between gradient pressure and speed in perforated 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 a variety of visual factors such as viscous forces and other forces arising from the spatial pressures between liquids and solids and spatial inconsistencies between different phases of liquids. The flow process is involved in the model using the pressure equation, but it takes further simulated analysis to solve the pressure figure instead of Darcy's calculation. For this reason Darcy's equation is widely used to mimic the flow of fluid through pore media.

2. Governing Laws and Equations

The basic law for controlling the flow of fluid through the hollow media was a law by Darcy given to Henry Darcy in 1856 on the testing of vertical water filtration using sand beds. Extensive distribution-related research was conducted by R. W Zimmerman in 2002 [14]. Darcy gave the equation as follows:

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

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]

A consistent set of units was used in Darcy's law as units of SI, C.G.S. units etc. In the oil industry the "local area units" are often used, which are not compatible. Darcy's law is similar to other mathematical laws in a series of mathematical terms, such as Ohm's law of electricity, Fick's law of solute diffusion and Fourier's law of driving heat. By the rules of fluid mechanics we know that Bernoulli's equation is as follows:

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

where P / ρ is related to the enthalpy by the unit of weight, g z is the gravitational force per unit of weight, v2 / 2 is the kinetic force per unit of weight. But the fluid speed in the pond is low so the third time will not be visible. We also see that the word (P – g z) represents the name of a kind of power. So it seems logical that the liquid could flow from high power regions to reduce the force so the driving force of the flow should be a gradient of (P - zg z). But because of Darcy's theory, it has been found that all components are equal, Q differs in contrast to the viscosity of the liquid. It is now advisable to specify the word μ, and then set C = k / μ, where k is known as accessibility. By taking the volume flow of each area of the unit, i. e., q = Q / A. Darcy's law can therefore be expressed as follows:

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

Where flux q has the dimensions of [m/s]. It is now easier to say of the units as [$m^3/m^2 s$].

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

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

Where suffix v is using for vertical flow. The negative sign is taken due to the fluid flows in direction from higher potential to lower potential. The differential form of the Darcy's law for one dimensional horizontal flow will be

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

When the suffix v is taken a direct flow. In many cases the ability to enter kh in a horizontal plane is different from direct entry, k_v; in these cases, $k_h > k_v$. The permeabilities in the two orthogonal directions within the horizontal plane have some differences. Then in that lesson we will take it in general: $k_h = k_v$. Permeability is a specific function of a rock type and varies according to temperature, pressure, etc., but is independent of the liquid; the effect of fluid due to the flow rate is calculated by the term viscosity in the above figures. Permeability has m^2 units, but in mathematical sense it is often used as "Darcy" units, defined as:

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

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

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

where d is the diameter of the pores. The permeabilities of various types of soils and rocks vary over many orders of magnitude. Then the permeabilities of petroleum reservoir rocks lie in the range of 0.001-1.0 *Darcies*. So it is suitable to refer the permeability of the reservoir rocks in the units of "*milliDarcies*" (*mD*) that equal 0.001 *Darcies*. In many reservoirs, the permeability is mainly due to an interconnected network of the fractures. The permeabilities of the fractured rocks lie in the range 1 *mD* to 10 *Darcies*. In the fractured reservoir, the reservoir scale permeability is not much related to core scale permeability, so that anyone can measure it.

If the fluid is in the static equilibrium then we have $q = 0$, hence the differential equation can be written as:

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

If we put $z = 0$ i.e., at sea level, where fluid pressure is equal to atmospheric pressure, then we can write

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

where P_s, P_a show the static pressure and atmospheric pressure respectively. But we always observe the pressure above the atmospheric pressure, so we can neglect the atmospheric pressure P_a in above equation (7). We can found by comparing equation (7) with equation (4) that only pressure above and beyond the static pressure given by equation (2) plays an important role in the derivation of flow. So the term ρgz is not of any use, as it only contributes to the static pressure and but does not play a role to driving force for flow. Then after neglecting the said term, the equation for correct pressure can be written as:

$$P_c = P - \rho gz \tag{8}$$

So the Darcy's law in 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 by using sea level i.e., $z = 0$, we can also 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 have

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

Choosing a data rate is not easy; means that it provides a constant time for adjusted pressure so as not to contribute to the pressure drop. The pressure Pc described in arithmetic (10) can be interpreted as the pressure of the analytical fluid at $z=z_o$ depth which will be in equilibrium and fluid and present at the actual pressure at 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 entry into the water storage area, we will not be referring to the entrance to the limited area of the figures as the given point can be a grain of sand and not a hole. Entry is now defined as a hole, not a single hole. Accessibility is therefore an asset in the definition of area measurement in an area around a point (x, y, z). Now the region should be large enough to cover a large number of pores. The P pressure applied in Darcy's law is primarily the central pressure taken from a small area of space.

Darcy's law does not provide sufficient information for time-based calculations i.e., temporary problems involving groundwater flow. So in order to get a complete statistical rule that applies to these types of problems, we can first get a statistical expression for the bulk conservation goal. Bulk savings statistics mean the balance between weight change rate and restricted volume and weight entry in the boundary area. In the main form we can write the following:

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

In the above equation the double and triple integrals are taken over the surface and the volume respectively and $\bar{v}$, $\bar{n}$, ρ, 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 equation (11) can be changed into the volume integral form by 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 conservation law can be

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

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

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

For the multiphase phase flow, it is necessary to account for saturation of each phase. So that the equation (14) within the every 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 Radial Coordnates

The transient flow of fluid in a pore space is controlled by a type of differential component known as the diffusion equation. Detailed discovery and distribution-related discussion was provided by R. W. Zimmerman in 2002 [14] that is, discussed in this paper as follows. So in order to get the figure, we combine Darcy's law with the law of mass conservation and the figure that describes the process by which the liquid is stored inside a perforated stone. Now we use the product function division (ρ ϕ), we find

$$D(\rho\,\phi) = \rho\, D\phi + \phi\, D\rho, D \equiv \frac{d}{dt} \tag{16}$$

$$= \rho \frac{d\phi}{dP}\frac{dP}{dt} + \phi \frac{d\rho}{dP}\frac{dP}{dt}$$

$$= \phi\left[\left(\frac{1}{\phi}\frac{d\phi}{dP}\right)\frac{dP}{dt} + \rho\left(\frac{1}{\rho}\frac{d\rho}{dP}\right)\frac{dP}{dt}\right]$$

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

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

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

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

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

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

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

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

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

But we know that,

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

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

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

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

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

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

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

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

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

$$d = \sqrt{4\, D_H t} \tag{25}$$

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

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

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

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.

In the field of engineering there is much interest in the case of fluid flow towards a well, in which case it is more convenient to use the cylindrical (radial) coordinates in the place of Cartesian coordinates. To derive the diffusion equation in radial coordinates, it is considered that the fluid flowing radially towards (or away from) a vertical well, in the radially symmetric manner. Now replace x with R, and taking $A(R) = 2\pi RH$:

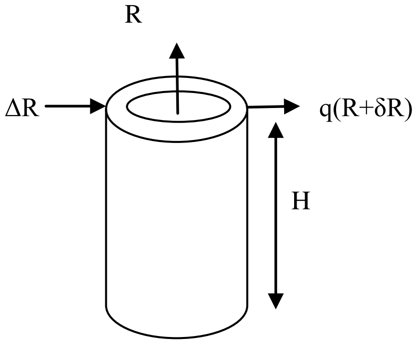

Fig.1 (A region used in deriving the diffusion equation in radial coordinates)

$$[2\pi RH\,\rho(R)\,q(R) - 2\pi(R+\delta R)\,H\,\rho(R+\delta R)\,q(R+\delta R)]\,\delta t = m(t+\delta t) - m(t) \tag{36}$$

Now dividing the above equation by δt, and taking limit as $\delta t \to 0$, we have

$$2\pi H\,[R\,\rho(R)\,q(R) - (R+\delta R)\,\rho(R+\delta R)\,q(R+\delta R)] = dm/dt \tag{37}$$

On the right-hand side:

$$M = \rho\varphi V = \rho\varphi 2\pi HR\,\delta R \tag{38}$$

$$\frac{Dm}{dt} = \frac{d(\rho\varphi 2\pi HR\,\delta R)}{dt}$$

$$\frac{Dm}{dt} = 2\pi HR\frac{d(\rho\varphi)}{dt}\,\delta R \tag{39}$$

Equate eqs. (37) and (39), divide by δR, and taking $\delta R \to 0$, we have

$$-\frac{d(\rho qR)}{dR} = \frac{Rd(\rho\varphi)}{dt} \tag{40}$$

Eq. (40) is the radial flow version of the continuity (*i.e.,* conservation of mass) equation. Now use the Darcy's law we have

$$\frac{K}{\mu}\frac{d}{dR}\left(\rho R\frac{dP}{dR}\right) = \rho\varphi(c_f + c_\varphi)R\frac{dP}{dt} \tag{41}$$

Follow the same procedure, we have

$$\frac{1}{\mathrm{R}}\frac{d}{dR}\left(R\frac{dP}{dR}\right)+c_f\left(\frac{dP}{dR}\right)^2=\frac{\varphi\mu\left(c_f+c_\varphi\right)}{k}\frac{dP}{dt} \tag{42}$$

For the liquids, we again neglect the term $c_f\,(dP\,/\,dR)^2$, to arrive at

$$\frac{dP}{dt}=\frac{k}{\varphi\mu c_t}\frac{1}{R}\frac{d}{dR}\left(R\frac{dP}{dR}\right) \tag{43}$$

Eq. (43) is the governing equation for transient, radial flow of a liquid through porous rock.

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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