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Study on Physical Dimensions of Some Expressions of Petrophysics

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Abstract: This study arose during the survey of a large number of works aiming to prepare a permeability model that presented a better accuracy than those consecrated in the literature for different types of reservoir rocks in the petrophysical area. The methodology used was to appreciate the mathematical expressions replacing physical quantities by their dimensions in the LMT system. After replacing length by L, mass by M and time by T, we compare the first members of the equations with the second to verify the homogeneity of the magnitudes involved in each mathematical formula. When these expressions are tested with experimental data, were identified formulas that did not show equilibrium in dimensions of their magnitudes, where it was observed that the permeability values found did not exhibit units of squared length. It has been used the phase spatial encoding in the Nuclear Magnetic Resonance Tool with experimental data of porosity, irreducible fluid volume, free fluid volume and transverse relaxation time. This distortion led us to conclude that the equations did not present their homogeneous physical dimensions, motivating a deep study in the identification of expressions used in the permeability calculation, in sandstone and carbonate rocks, with no equilibrium in their dimensional equations in any unit system. This review aims to identify the constants used in the equations equilibrium suggesting modifications that can be obtained through pre-established relationships to increase the reliability of the equations previously used.

Keywords: Porosity, Permeability, Dimension, Equilibrium Equation, Nuclear Magnetic Resonance, Phase Enconding

1. Introduction

1.1. Objective

The objective of this paper is to investigate the lack of rigor in the balance of physical dimensions in some formulas published in works in the petrophysical area. This study is intended to assist the adequacy of mathematical terms of some formulas used to express quantities of interest, such as: permeability, porosity, diffusion coefficient, resistivity, and the surface relaxivity. Some publications use expressions in that its terms are multiplied by constants which are not accompanied by their respective units. It is suggested in this paper that these constants have their units cited, for a better understanding of the reader. It is expected to contribute to a better accuracy and understanding in the determination of some quantities which are important for the study of petrophysics.

1.2. Literature Review

During investigations for the preparation of the final work of doctoral studies, it was observed that some equations which are widely used in the petrophysical area were not with their physical dimensions homogeneous and thus, encouraging us to better understand the use of these equations without being dimensionally appropriate. Some of these articles offer expressions or terms whose dimensions are not in accordance with the common dimensional rules.

On account of these observations, a review was made on these dimensional adaptations and a brief discussion of some examples found in the literature [4, 10, 16].

2. Dimensional Equations

2.1. General Concept

It is called the physical units system the set of units used to measure all species of physical quantities. It has been found that the units of a system could be defined in terms, express or implied, of at least six units, since they were conveniently chosen. These six units are regarded as the fundamental units, or primary of the system, being set arbitrarily. The other units, which are considered derivatives, or secondary, are defined on the basis of the fundamental units. We say that a system is consistent when their units are defined on the basis of a small number of units, arbitrarily chosen as fundamental. The arbitrariness in the choice of the fundamental units of a system is not complete. There are some conditions that must be fulfilled [4, 16, 21].

a) the fundamental units must be independent of each other;
b) the value of a fundamental unity must be invariant;
c) the fundamental units can be represented by a pattern;
d) the fundamental units allow an easy and direct measurement of the quantities of their species.

2.2. System of Mechanical Units. The LMT and LFT Systems

A system of physical units gathers geometric, kinematics, dynamics, thermal, electromagnetic, thermodynamics and optics units. The basic units are the geometry, kinematics and dynamics ones. In such systems, it takes only three units - a geometric one, a kinematic one and a dynamic one [8, 10].

All systems used today adopt the length as fundamental geometric quantity and time as fundamental kinematic quantity, representing symbolically the length by L, mass by M, and time by T, we can group systems, now used in two general types: MLT and LFT. The MLT systems are also called inertial or physical systems and the LFT systems are called gravitational or technicians systems. Systems of the LMT type use the length (L), mass (M) and time (T) as fundamental quantities and those of LFT type use the length, the force and time, being the MKS system of LMT type. Its fundamental units are the length in meters (m), the mass in kilograms (kg), and the time in second (s) [8, 11, 19, 21].

2.3. Definition Formula of a Quantity

For a formula is established the correlation of quantity considered in relation to the other, depending on which the first one was defined. The formula expressed in mathematical language the given definition, conventionally, for a quantity [8, 16].

Be the quantity G defined in terms of the quantities A, B and C, the formula:

$$G = k\, A^a B^b C^c \tag{1}$$

Maxwell proposed to represent the dimensions of the quantity G by the symbol [G]. Similarly, the dimensional symbols of the quantities A, B and C are respectively [A], [B] and [C]. Using the dimensional symbols the previous equation acquires looks as follows [8, 16]:

$$[G] = [A]^a.\, [B]^b.\, [C]^c \tag{2}$$

This equation that relates the dimensional symbols of a certain quantity with the dimensional symbols of the quantities that the first depends on, receives the name of DIMENSIONAL EQUATION of considered quantity [10, 16].

The exponents a, b and c, which appear in the dimensional equation of G are called dimensions of quantity G in relation to the quantities A, B and C, respectively. The concept of dimensional equation is independent of the nature of the quantities A, B and C in relation to which it was determined the dimensional equation [G] Equation 2. In practice, write dimensional equation of quantities in relation to the fundamental quantities of the systems of the LMT type [8, 10, 11, 19].

"It should be noted that every magnitude or indeterminate constant has a dimension of its own, and that the terms of an equation cannot be compared if they do not possess the same exponents of dimension. We introduced this account in our theory of heat to make our definitions more accurate and to serve as a check of the analysis; it is derived from primary notions about quantities, which is why, in geometry and mechanics, it is the equivalent of the fundamental slogans that the Greeks left for us without evidence" [10].

3. Dimensional Analysis of Quantities Used in Some Works

For the analysis of some equations, we need to determine the size of some quantities. Then, there will be a dimensional analysis of porosity (φ), permeability (K), time (T), diffusion coefficient (D) and the superficial relaxivity (ρ), because these quantities will form the basis of this study.

3.1. Porosity (φ)

The porosity is defined as the ratio between the pore volume (V_p) and the total volume (V_t) of the sample, and it is given by the expression 3.

$$\emptyset = \frac{V_p}{V_t} = \text{dimensionless} \tag{3}$$

Since it is defined by the division in two volumes, this is a dimensionless quantity.

3.2. Permeability (k)

The permeability was defined from the Darcy's law, as it is expressed below [5, 22, 28, 29, 30].

$$Q = \frac{AK}{\mu} \cdot \frac{dP}{dX} \quad (4)$$

Explaining K in equation 4, we have:

$$K = \frac{Q.\mu.dX}{A.dP},$$

where:

$$[Q] = \frac{L^3}{T}$$

$$[\mu] = \frac{\frac{ML}{T^2}T}{L^2} = \frac{M}{LT}$$

$$A = L^2$$

$$[dX] = L$$

$$[dP] = \frac{\frac{ML}{T^2}}{L^2} = \frac{M}{T^2L}$$

Putting the equations above at 4, we have:

$$[K] = L^2 \quad (5)$$

3.3. Time (T)

Whatever the measure is, its dimensional equation will be:

$$[T] = T \quad (6)$$

3.4. The Diffusion Coefficient (D)

The equation of diffusion to the uniform density is given by:

$$\frac{\partial \delta(x,t)}{\partial t} = D.\nabla^2 \delta(x,t) \quad (7)$$

Through simple calculations, it can be concluded that the diffusion coefficient has size $L^2 T^{-1}$, therefore:

$$[D] = L^2T^{-1} \quad (8)$$

3.5. Superficial Relaxivity (ρ)

Using the fundamental ratio between T_2 and ρ [1, 2, 9, 21], given with estimates for:

$$\frac{1}{T_2} = \rho_2 \frac{S}{V} \quad (9)$$

Being T_2 the transverse relaxation time, S the surface area of the pore and V the volume. By simple observation, it can be concluded that the size of ρ is L/T or LT^{-1},

$$[\rho] = \frac{L}{T} \quad (10)$$

4. Expressions with Non-Homogeneous Dimensions

After an extensive literature review there were identified some expressions containing terms whose equations are not balanced. There is no concern about putting them in Chronological order, but rather to identify them with the goal of providing their authors and readers a critical position on this matter, in order to provide a new approach on the accuracy in applying these expressions.

Latour et al. describes the expression, for short intervals of time, where the size of the fourth term does not match the size of the diffusion coefficient, namely [3, 15]:

$$D(t) = D_0 \left(1 - \frac{4}{9\sqrt{\pi}} \frac{\sqrt{D_0 t}\, S}{V} - \frac{S}{12V} \langle \frac{1}{R_1} + \frac{1}{R_2} \rangle D_0\, t + \frac{1}{6} \frac{\rho S}{V} D_0 t\right) \quad (11)$$

It can be considered then the size of the fourth term as dimensionless, because all terms are multiplied by D_0.

$$\frac{1}{6} \frac{\rho S}{V} D_0 t = A$$

$$[A] = \frac{\frac{L}{T} L^2}{L^3} \frac{L^2}{T}\, T = \frac{L^2}{T} \quad (12)$$

Then this equation is not homogeneous. When you observe the dimensional adjustment of other terms, it can be concluded that all are dimensionless, except the fourth term.

In the same article [15], the expression for very large times features:

$$\frac{D(t)}{D_0} = \frac{1}{\alpha} + \frac{\beta_1}{t} + \frac{\beta_2}{t^{3/2}} \quad (13)$$

It is observed that the term on the right-hand side of equality is dimensionless. The first term on the left side is also dimensionless because "α", the tortuosity is given by the ratio between the path followed by the fluid (L) and the length of the sample (L). The terms two and three have dimensions, since β_1 and β_2 are constants that depend on microscopic details and or the lithology of the specimen of rock. In order to comply with the homogeneity of the Equation 13, β_1 must have size T^1 and β_2 size $T^{3/2}$.

4.1. Kozeny-Carman Permeability Equation

The Kozeny-Carman equation [6, 18, 24], is used to determine the permeability K_{KC} and it is given by the following expression:

$$K_{kc} = \frac{1}{F_s \tau^2} \frac{\emptyset_{eff}^3}{(1-\emptyset_{eff})^2} \frac{1}{S_g^2} = a\emptyset_{eff}^b \left(\frac{V}{S}\right)^c \quad (14)$$

It can be observed that the first equality is dimensionally correct, but the second equality will only have correct dimension if the coefficient c is equal to 2. It is possible to argue that the constant pre-multiplier may have size, but to balance any value of the constant c, in accordance with dimensional terms, it should vary for each rock analyzed, since the literature states that a, b and c are coefficients that depend on the lithology [1, 2, 4, 19, 23]:

In the literature [4, 17, 19] we have the following expressions:

$$T_{2D} = \frac{3}{\gamma^2 G^2 D \tau^3} \quad (15)$$

and,

$$\frac{1}{T_{2diffusion}} = \frac{D(\gamma GTE)^2}{12} \quad (16)$$

Calculating the dimensional equations, it is concluded that:

The first member of the equation 15 is size T and the second member is dimensionless, i.e., it has zero dimension.

In the equation 16 the first member has dimension 1/T and the second one also has dimension 1/T. This is the dimensionally true equation.

4.2. Timur – Coates Equation [13, 19, 23, 24]

$$K_{TC} = a\left(\frac{FFI}{BVI}\right)^b \emptyset^c \quad (17)$$

The dimensions of the terms of the equation are:

$$[K_{TC}] = L^2 \quad (18)$$

$$\left[\frac{FFI}{BVI}\right] = \text{dimensionless} \quad (19)$$

$$[\emptyset] = \text{dimensionless} \quad (20)$$

Therefore,

$$[a] = L^2 \quad (21)$$

4.3. SDR Equation for Sandstone, [17]

$$K = T_1^2\emptyset^4 \quad (22)$$

$$[K] = L^2 \quad (23)$$

$$\left[T_1{}^2\right] = T^2 \quad (24)$$

$$[\emptyset^4] = \text{dimensionless}$$

In other words, this equation does not present the balance aspect expected.

Seever equation of $T_{1,2LM}$ [1, 23, 27].

$$T_{1,2LM} = exp(\langle logT_{1,2}\rangle) = exp\left(\frac{\Sigma\phi_i logT_{1,2i}}{\Sigma\phi_i}\right) \quad (25)$$

The equation 25 was proposed by Seever in 1966 [23] to express the average value of relaxation times. It was used in several articles and has as its unit the second submultiples. But making a dimensional analysis it can be seen that $T_{1,2LM}$ has no size T, i.e..

$$[T_{LM}] \neq T \quad (26)$$

So, what would be the unit of $T_{1,2LM}$?

The experiment of Kenyon et al. [12] based on the analysis of hundreds of samples of sandstone has proposed an expression for the permeability called SDR equation. Arns and Meleán [1], as well as Rios [18], suggests to the classical model of equation 27, when a=1, that its unit would be the superficial relaxivity squared, but shortly thereafter, suggests that a is given by $a = \frac{1}{(6\rho)^2}$, causing the expression losing its homogeneity [12, 26].

$$k_{SDR} = a\phi^4 T_{1LM}^2 \quad (27)$$

For the second member to have dimension L^2, the constant must have dimension L^2/T^2, but the majority of articles presents the constant as dependent on the lithology of rock and does not comment on what its unit is.

$$[a] = \frac{L^2}{T^2} \quad (28)$$

For the sake of ease and rapidity, T_{1LM} was replaced by T_{2LM} in K_{SDR} expression, and the following expression was formulated.

$$K_{SDR} = a\emptyset^b T_{2LM}^c \quad (29)$$

The analysis shows us that the second member of the Equation 29 should submit the dimension L^2. To this end, the constant a must have size L^c/T^c, causing the dimension of a to depend on the value of the constant c.

Souza et al. [27] proposed a new model for the permeability, Kρ, which takes into account, through the superficial relaxivity (ρ), the interaction of the walls of the pore with the fluid, equation 30 [5, 26, 27].

$$\kappa_\rho = a\phi^b(\rho_2 T_{2LM})^c \quad (30)$$

In this new situation, it has been:

$$[\rho_2] = \frac{L}{T} \quad (31)$$

Within this aspect it is possible to make the following considerations:

a- If the constant "c" assumes the value of 2, the constant "a" will be dimensionless;

b- If the constant "c" assumes any value other than 2, the constant "a" will be the dimension $[a] = L^{-(c-2)}$.

The work developed by Silva [25], proposed the expression of the permeability as a function of magnetic susceptibility, equation 32, given by:

$$K_{SDR} = a\emptyset^b T_{2LM}^c \Delta\chi^d \quad (32)$$

In this same article it was made available a table, in which the unit of susceptibility in the international system appears as m^{-3}. Admitting this unit as correct, it can be concluded that the size of the susceptibility is:

$$[\chi] = L^{-3} \quad (33)$$

Calculating the dimensional equation for K_{SDR}, it is concluded that the Equation 32 will only be dimensionally balanced if the constant "a" presents dimension.

$$[a] = \frac{L^{(2+3d)}}{T^c} \quad (34)$$

However, according to Sears [22] and Laranja [14], the unit of susceptibility appears as:

$$[\chi] = \frac{\text{Henrys}}{m} = ML^2Q^{-2} \quad (35)$$

Where Q represents the charge. In this case, the Equation 32 does not have homogeneous dimensions.

It can be observed that in the case that "d" takes the value of zero; the Equation 32 is reduced to equation of classical K_{SDR}, Equation 27.

4.4. The Winland Method

This method relates the radius to 35% of the maximum value injected mercury, pore volume with the permeability K_{R35} and the porosity φ [23, 25, 28]. Its expression is presented below:

$$\text{Log}R_{35} = 0{,}732 + 0{,}588K_{R35} + 0{,}864\log\Phi.$$

Assuming,

$$[\text{LogR}_{35}] = \text{L} \tag{36}$$

$$[\text{K}_{\text{R35}}] = \text{L}^2 \tag{37}$$

$$[\emptyset] = \text{dimensionless}$$

Therefore,

$$[\text{LogR}_{35}] \neq [\text{K}_{\text{R35}}] + [\phi] \tag{38}$$

The equation of the Winland method has no balance in their dimensions.

4.5. Swanson's Method

This method uses results of the mercury intrusion to calculate the permeability and its equation is given by Equation 39 [7, 25, 30]:

$$\text{K}_{\text{Sw}} = \text{a}\left(\frac{\text{S}_{\text{Hg}}}{\text{P}_\text{c}}\right)^\text{b} \tag{39}$$

Thus, S_{Hg} the mercury saturation and P_c its corresponding capillary pressure. The dimensional equation takes the following form.

$$[\text{S}_{\text{Hg}}] = \text{dimensionless} \tag{40}$$

$$[\text{P}_\text{c}] = \text{M}\frac{\text{L}^3}{\text{T}^2} \tag{41}$$

Replacing the Equations 40 and 41 in Equation 39it has been:

$$[\text{K}_{\text{sw}}] = \text{a}\frac{\text{T}^{2\text{b}}}{\text{M}^\text{b}\text{L}^{3\text{b}}} \tag{42}$$

So that the dimension of equation 39 is correct the constant a must have the following expression:

$$[a] = \frac{M^b L^{(2+3b)}}{T^{2b}} \tag{43}$$

M is the mass, T is the time and L is the length.

Then the Equation 39, whose dimensional equation is given by Equation 42, is not homogeneous.

Robinson et al. [20] describes an empirical expression for the velocity V as a function of the rock porosity Φ, Equation 44, as follows.

$$\text{V} = 0{,}0600 + 0{,}0110\emptyset - 0{,}000524\emptyset^2 + 0{,}00000827\emptyset^3 + \cdots \tag{44}$$

Of the Equation 1 it is known that Ø is dimensionless, so all the power of Ø are also dimensionless. Therefore, the Equation 44 is not dimensionally correct, because the dimension of V is given by:

$$[V] = \frac{L}{T} = LT^{-1} \tag{45}$$

5. Conclusions

The dimensional analysis can be considered one of the checks to the ascertainment of the accuracy of an equation involving physical quantities [22]. However, satisfying the condition of dimensional balance does not imply that the formula relates with accuracy the main quantities and derived from this formula.

In this literature review, it is intended to draw the attention of those factors related to physical dimensions, with the aim of making the expressions, empirical or theoretical, more accurate in determining the parameters of interests of petrophysics.

In this study, we could observe in equations, which are of common use in petrophysics, the need for adjustments to meet the homogeneity in their physical dimensions. In some situations, to correct these failures, one can inform, in the texts, units of constant adjustment of the experimental values and/or mathematical. It is intended, finally, in this review, pointing out the concern in the observation of units in these works, so that the reader can have more precise information about the searches carried out.

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