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A NEW METHOD OF PRESSURE DROP MODELLING IN SANDSTONE ROCKS

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Abstract
Production capacity of any hydrocarbon reservoir is the most important question that needs to be answered. This depends on both the obtainable drawdown between the well and reservoir and the petrophysical properties (pore size distribution, wettability properties, saturations etc.) of the porous rock material. Permeability, introduced by Darcy is the parameter describing restrictions present during fluid flow in porous media. Although this method is the one currently accepted and implemented in the industry it has a major flaw because it considers flow in the geometric (total) rather than the effective volume, where it truly develops. During this study a new approach of flow restriction modelling was found, where flow restrictions, measured from sandstone plug samples were compared with the theoretic flow volumes which are equal to the total pore volumes, constructed of steel capillaries of equal diameter. Results show that flow restrictions of incompressible fluids in sandstone can be demonstrated by the new model.

Keywords: *porous system, petrophysical properties, permeability, modelling, steel capillaries*

1. Introduction

What is the most important question that needs to be answered for any hydrocarbon reserve? Production capacity of a well depends on both the obtainable stable fluid flow rate entering the well-bottom at the developed drawdown (the pressure difference between the flowing bottom hole pressure and pressure of the reservoir) as well as the petrophysical properties (also known as macroscopic properties) of the reservoir. Multiple effects take place in the characterization of the well inflow performance (formation damage, cementing, perforation), during the drilling and finishing works.

From a petrophysical point of view many parameters effects fluid flow in the porous system. Of which the most characteristic are pore size distribution, wettability properties, and the saturation levels of different fluids to name a few. The inflow performance of a well can be described as the cumulative effect of these parameters in function of the existing pressure drawdown between the well and the reservoir. Darcy (Darcy, 1856) introduced an equation based on experimental results (made on sand beds) describing the ability of a porous medium to allow the flow through of incompressible fluid in its volume. This formula is now known as Darcy's law and as referred as permeability (k).

Although this method is the one currently implemented by the industry it has a major flaw, considering flow development across the geometrical cross-sectional area of the studied volume rather than the effective one, where flow truly happens.

The presentation of a new approach for flow restriction modelling rather than Darcy's solution was the aim of this study. The introduction of a theoretical volume matching the total pore volume, constructed from steel capillaries of equal diameter. The number and diameter of the capillaries were determined by an iteration process where the sum of the pressure drops across all capillaries equal to the value appearing at 100% water saturation and steady state condition during absolute permeability measurement. Thus, representing a more reliable solution for reservoir and production modelling while solving the issue of insufficient description of Darcy's method regarding production capacity.

During the examination the working model was developed and was validated using data gathered from petrophysical measurements performed on sandstone plug samples drilled from a reservoir located in Hungary.

2. Examination

Flow restrictions of fluid in porous material were examined in the past by many but one of the first solutions that was made belonged to Darcy, (Darcy, 1856) who introduced the equation of single-phase filtration valid for incompressible fluids. Although this solution reached satisfactory conditions it did so by implementing many simplifications.

Let's consider a certain volumetric element with fixed boundaries in space as Heinemann (Heinemann, 2005) suggested. This cylindrical shaped volume must be chosen in such way that:

1. The random effects could be eliminated statistically
2. The studied surface is built up of streamlines and the base surfaces are perpendicular to those lines. The length of the streamlines is δs with the cross section of the volume is δA.
3. Regarding the control volume, all forces acting on the fluid body are equal.
4. As Newton's Law of motion states, a fluid body will accelerate until resultant acceleration is larger than zero but will keep its velocity (u_i).
5. We seek a value for u_i such that the resultant acceleration equals the null vector.
6. In order of achieving simplicity without losing generality, a cylindrical element was taken as control volume.

In this control volume two kind of forces are present, those acting on the fluid body and others on the fluid surface. During the filtration of fluid, the most important forces needed to be mentioned are the following. Forces of gravity and inertia are acting on the fluid body, while the Forces of compression, friction and capillary are considered surface forces. In case of low velocity single-phase filtration some of these forces could be taken out of the equation simplifying it.

During the steady state flow conditions, the convective and local acceleration of the fluid can be considered infinitesimal, in result Forces of inertia can be neglected. Capillary forces are present between two immiscible fluids separated by an interface in the pore channels. In the case of one phase filtration, capillary forces are disregarded from the equation, and are only applied if the water-bearing layer does not have a saturation level of 100%.

In result only the forces of compression, gravity, and friction, are considered, which are all proportional to the velocity of filtration. In such the force equilibrium can be written up as shown by *Equation 1*.

$$F_{pres} + F_{grav} + F_{visc} = 0 \tag{1}$$

This force equilibrium state written in form of the previously specified volumetric element result in *Equation 2*. Where $\phi\delta A$ represents the pore surface (the effective cross section) of the volumetric element while $\nabla p\delta s$ describes the pressure difference present along the length of the control volume. Also, the unit vector directed upwards is presented by i_3 while μ is the dynamic viscosity *(cP or mPas)* and ρ is the density (*kg/m*^{3}) of the fluid. After some rearrangement *Equation 3* can be written up in which two parameters must be presented.

$$-\phi\delta A\nabla p\delta s - \rho g\phi\delta A i_3\delta s - B\mu\delta A u\delta s = 0 \tag{2}$$

$$-\left(\nabla p + \mu\frac{B}{\phi}u + i_3\rho g\right)\phi\delta A\delta s = 0 \tag{3}$$

These so called petrophysical parameters are porosity (ϕ) and the coefficient of the given porous media (*B*). As shown in *Equation 3* flow develops in the effective cross-sectional area a section of the absolute (total) cross section of the porous material.

This effective volume occupied by the fluid due to the complexity of the porous network is truly troublesome to describe thus was eliminated from the differential form of Darcy's equation. In result Darcy's solution was found in the ratio of ϕ/B known as permeability (*k*, in *D*) presented in *Equation 4*. In this form permeability presents the restrictions fluids face during their flow in the porous material. In result permeability is the property of the given material meaning that its value for all non-reactive fluid will be equal.

Permeability shortly became the most crucial parameter regarding production capacity determination in the petroleum industry, required in all reservoir simulations despite its main flaw on implementing the total cross-sectional area of the porous sample rather than the effective one (*Equation 5*). This resulted in giving unreliable information on its own on the system's capacity due to the lack of other petrophysical parameters such as pore size distribution (Bear, 1972) wettability and tortuosity (Erle et al., 1973) and many more. The absolute permeability of porous samples regarding 100% saturation of a given incompressible fluid can be determined implementing laboratory measurements applying *Equation 5*.

$$u = -\frac{k}{\mu}(\nabla p + i_3\rho g) \tag{4}$$

$$k = \frac{q\mu l}{A\Delta p} \tag{5}$$

In laboratory and industry cases the application of *mD* for unit is preferred over *D* because in cases of well consolidated rock material permeabilities over *1D* are not common. In order to receive permeability in *mD* in such measurements the parameters present in *Equation 5* need to be in the following units. Flowrate *cm*^{3}*/s*, dynamic viscosity either *cP* or *mPa s*, the length (height) and surface area of the cylindrical sample is in *cm* and *cm*^{2}, and the pressure difference along the sample is in *atm*.

This led to the consideration that during the study a method where the effective volume is implemented should be prioritized when describing the restrictions of fluid flow, resulting in a much more reliable presentation of the complexity of these systems.

3. Solution

Darcy as mentioned previously described flow in the total cross section on purpose due to the fact that the pore systems of reservoir rocks are rather chaotic consisting of spatial network of larger pores (pore bodies) connected by finer pores (pore throats) as described by Stig et al., 1997. Due to the lack of necessary tools required there was no other choice but to do so. Macroscopic properties such as absolute, effective and relative permeability, capillary pressure, formation factor and resistivity index are determined by the architecture and geometry of the pore network and its complementary grain matrix.

Many studies were presented where the attempt was made to describe the porous systems of sandstones and other hydrocarbon bearing rocks. A rather commonly used method uses the implementation of network flow simulators (network models). Such models were applied with sufficient results assuming the presence of simple or idealised porous media (Chan et al., 1988) using pore-scale physics identified in micromodels (Li et al., 1986) in the past, even in two-phase flow cases. Although this kind of approach requires detailed understanding of the physical processes present on pore scale also the complete description of the pore spaces morphology. (Stig et al., 1997) had presented their new method for generating realistic and fully characterised 3-D pore networks. This method is based on numerical modelling of the results of the main sandstone-forming geological processes. The network representation of the pore space of the modelled sandstone was extracted from its complementary mineral matrix network using image analysis techniques. During this work fluid flow simulations were performed directly on the irregular pore network and the computed transport properties were validated using experimental data.

A scientific model represents an approximation or simulation of a real system that omits all but the most essential variables. In other words, it describes reality implementing rules defined by the operator to reach satisfactory results. The previously mentioned methods require such equipment and techniques not to mention calculating capacity that are usually inaccessible. Also performing the above mentioned difficult and time-consuming procedures will result only in the model of a significantly small volume of the porous sample. It could be clearly seen early on during the investigation, that a new approach was needed other than petrophysical, to define the basic principles on which the model works in order to be able to reach those volumes of the actual reserves.

As previously mentioned, from a production point of view, the capacity of a well can be described as the function of both the petrophysical properties of the rock and the drawdown achievable at a given stable production rate. To put it simply, production is the function of the pressure difference present during incompressible fluid flow in a porous material at a predetermined stable flowrate. Because of this fact, throughout the work, the modelling of the pressure loss of the system was considered as the objective.

Thereby a solution was found where the effective volume of the system was constructed of a given number of steel capillaries (c), equal in diameter (d_c) which would match the pressure loss measured during the absolute permeability measurements. The number and size of the capillaries are found by an iteration process where the sum of the pressure drops equal the pressure difference measured between the inlet and outlet sides of the samples at a chosen flow rate at constant flow conditions reached.

The calculation procedure of pressure drops (Equation 6) in smooth steel pipes is a rather simple one, where almost all required parameters are already known. Such as the geometry of the pipe (diameter d and length dl) and the properties of the fluid (density and viscosity at given pressure and temperature). The only parameters needed are the velocity (v) of the flow and the frictional factor (f).

$$\frac{dp}{dl} = \frac{g}{g_c}\rho \sin\alpha + \frac{\rho v dv}{g_c dl} + f\frac{\rho v^2}{2g_c d} \tag{6}$$

By assuming the developed flow to be steady state in horizontal position, the effect of potential and kinetic energy changes can be neglected because of their infinitesimal small values. This resulted in pressure drops caused only by irreversible energy losses of friction. During the calculation of pressure drops present in steel pipes those described by Takács (Takács, 2012), were used and altered to fit the new requirements. In this equation g_c represent a conversation factor of the value 32.2 (required in Field unit case), while α represents the inclination of the pipe. The chosen process begins with the calculation of the flow velocity regarding the pipe geometries at hand as well as the developed steady flow rate of the incompressible fluid presented by *Equation 7*. In which q_w is the developed flowrate (*STB/day*), d_i is the pipe inner diameter (*inch*), and B_w presents the formation volume factor of the fluid (*bbl/STB*), resulting in flow velocity (v) of *ft/s*.

$$v = 0{,}0119\frac{q_w B_w}{{d_i}^2} \tag{7}$$

The friction factor of the developed flow can only be determined after the developed flow region is known. Reynolds described the different flow regions of incompressible flow introducing the so-called Reynolds number (*Equation 8*), the ratio of internal to viscous forces (in the fluid of a given density of ρ_w, *lb/ft*^{3}) within the fluid subjected, to relative internal movement due to different fluid velocities. Depending on this number flow, can develop either laminar, transient, or fully turbulent flow characteristics. *Equation 9* is valid for laminar (N_{Re}<2300) region while at turbulent (N_{Re}>2300) cases other calculations are required. A diagram was developed by Moody where the value of frictional factor can be found regarding all flow types as a function of both the Reynolds number and the relative roughness (ε_{rel}, *inch/inch*). Calculated from the absolute roughness (ε, *inch*) of the pipe material and its internal diameter of the pipe (*Equation 10*). In possession of the *f* factor pressure losses, due to friction can be determined applying *Equation 11*.

$$N_{Re} = 124\frac{\rho_w v d_{ci}}{\mu_w} \tag{8}$$

$$f = \frac{64}{N_{Re}} \tag{9}$$

$$\varepsilon_{rel} = \frac{\varepsilon}{d_i} \tag{10}$$

$$\Delta p = 0{,}001294 f\frac{l}{d_{ci}}\rho_w v^2 \tag{11}$$

To alter the pressure, drop calculation of steel pipes to fit the new model where multiple capillaries are present and the total pressure drop (caused by friction) distributes in those, the following modifications were applied. At first the effective flow volume (pore volume) had to be defined where flow occur, presented as the sum of the capillaries of equal diameter:

$$V_p = l\left(c_i\frac{{d_{ci}}^2\pi}{4}\right) \tag{12}$$

$$V_p = V_b\phi \tag{13}$$

$$V_b = l\frac{{d_b}^2\pi}{4} \tag{14}$$

Deriving the final form of *Equation 12* the true pore volume ie. effective volume is defined as the left-hand side of *Equation 15* while the other side describes the effective volume implemented by the model. After reducing the equation by the parameters present on both sides *Equation 16* will present the simplest form of *Equation 12*.

$$\left(l\frac{{d_b}^2\pi}{4}\right)\phi = l\left(c_i\frac{{d_{ci}}^2\pi}{4}\right) \tag{15}$$

$${d_b}^2\pi\phi = c_i{d_{ci}}^2\pi \tag{16}$$

In order to simplify the calculation process, the right-hand side of the equation describing the model volume was regrouped (*Equation 17*) introducing a new "coefficient" (OP). Porosity, the diameter as well as the number of the capillaries constructing the pore volume could be determined as following.

$$OP = {d_{ci}}^2 c_i \tag{17}$$

$$\phi = \left(\frac{d_{ci}}{d_b}\right)^2 c_i = \frac{OP}{{d_b}^2} \tag{18}$$

$$d_{ci} = d_b\sqrt{\frac{\phi}{c_i}} \tag{19}$$

$$c_i = \phi\left(\frac{d_b}{d_{ci}}\right)^2 \tag{20}$$

Rewritten *Equation 7* describes the velocity of the incompressible fluid flow developed in a single capillary (v_c, *ft/s*) of the given diameter (*Equation 22*). Assuming equivalent distribution of fluid in all capillaries, flow rates regarding each capillary will be derived by *Equation 21* where q_m is the actual flow rate measured during the permeability measurement of the sample. In result the velocity of flow developed in each capillary (q_c, *STB/day*) of equal diameter can be described as presented by *Equation 23*.

$$q_c = \frac{q_m}{c_i} \tag{21}$$

$$v_c = 0{,}0119\frac{q_c B_w}{{d_{ci}}^2} \tag{22}$$

$$v_c = 0{,}0119\frac{q_m B_w}{{d_{ci}}^2 c_i} = 0{,}0119\frac{q_m B_w}{OP} \tag{23}$$

The presence of Laminar flow conditions was one of the terms determined by Darcy during his solution of single-phase filtration in porous media. This was also implemented in the new model. For stable flow rates which do not exceed laminar flow conditions, the Reynolds number regarding each capillary is calculated using *Equation 24*. Followed by the determination of the friction factor *Equation 9*.

$$N_{Re} = 124\left(\frac{\rho_w v_c d_{ci}}{\mu_w}\right) \tag{24}$$

From the friction factor, the pressure drop in a single capillary is calculated using *Equation 25*. This is then multiplied by the number of capillaries present equals the pressure drop of the total system (*Equation 26*).

$$\Delta p_c = 0{,}001294 f \left(\frac{l}{d_{ci}}\right) \rho_w {v_c}^2 \tag{25}$$

$$\Delta p_{c\_total} = c_i \Delta p_c \tag{26}$$

The procedure required a two-cycle structure, presented in ***Figure 1***, where as part of the primary iteration cycle a value for c_i is suggested, from which d_{ci} is calculated (*Equation 19*). After the value of inner diameter is determined the velocity of flow in a single capillary is calculated. At the final step of the cycle the values of ci and d_{ci} are verified (*Equation 24*). If the result of N_{Re} exceeds the limit of laminar flow condition (N_{Re}>2300), the cycle starts over by estimating a new capillary number (c_{i+1}) and repeats as previously described. At the satisfactory condition (N_{Re}<2300) the process continues further by starting the second cycle.

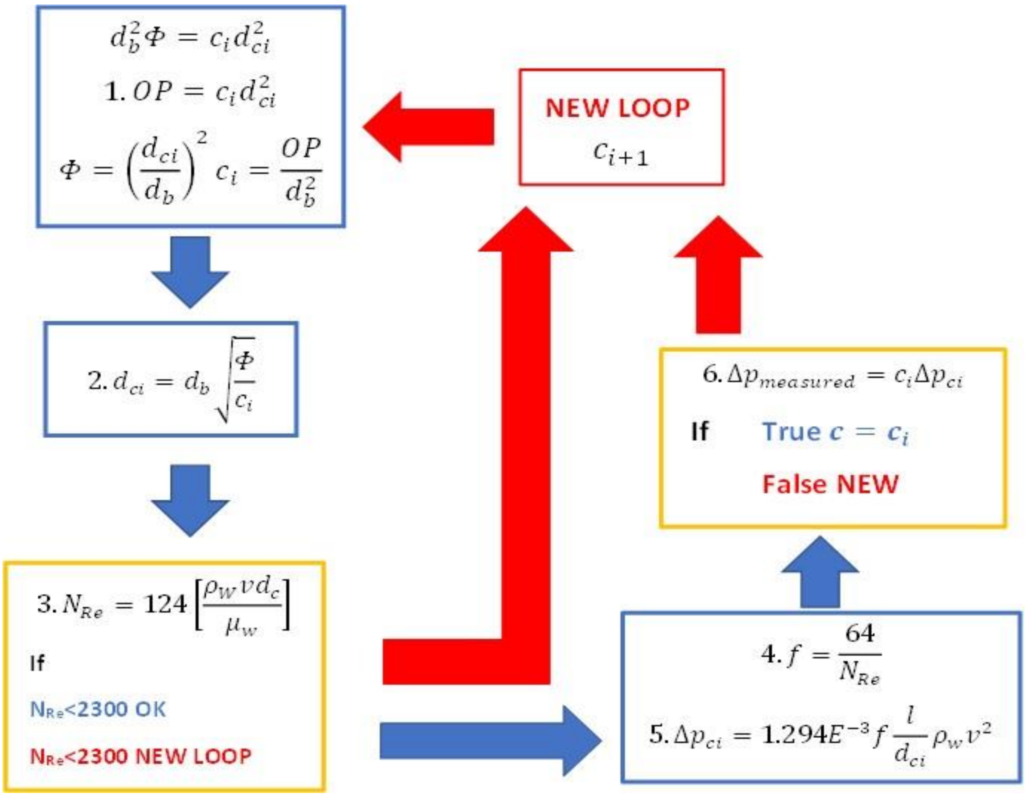

Figure 1. *The schematic figure of the calculation process*

At the second cycle, the values of c_{i+1} and d_{ci+1} are verified a second time throughout the calculation of the overall pressure drop in the capillaries. If the calculated pressure drop does not equal the one recorded during the absolute permeability measurement of the given porous sample, the procedure starts over from the first cycle estimating a new capillary number (c_{i+2}) and so on. The value of c and d_c are found in those values which fit both verification cycle.

The model was tested on multiple occasions, implementing data gathered from absolute permeability measurements made on consolidated sandstone sample plugs (total of 25 samples) of a Hungarian oil reservoir origin. The samples chosen for the measurements belonged to an extremely wide range concerning their absolute permeability (0,33-856,30mD).

This wide range assured the sufficiency of the new model. While the identical geological structure origin assured divergences other than rock diagenetic nature. The absolute permeability and porosity values of all samples are presented in ***Table 1*** via increasing permeability.

4. Results

During the study all results presented by the model achieved satisfactory conditions (***Table 1***). The calculated number and corresponding diameters of the theoretical steel capillaries met the criteria of both laminar flow profile (regarding the observed flow rates) while reaching relatively low divergences between the calculated (Δp_{c_total}) and measured ($\Delta p_{measured}$) values of pressure drops.

Table 1. *The results of the measured sandstone samples*

Sample ID	k_w, mD	Φ_{He}	q_m, stb/d	$\Delta p_{measured}$, psi	Δp_{c_total}, psi	N_{Re}	c	d_c, inch
S_9	0,33	0,1644	0,0041	179,1274	179,1274	2,6341	60601	0,00246
S_10	0,47	0,1522	0,0019	137,4897	137,4897	1,2095	67106	0,00223
S_11	0,72	0,2509	0,0045	106,2903	106,2903	2,3275	63160	0,00296
S_12	1,06	0,2617	0,0070	114,2719	114,2719	3,8552	54043	0,00325
S_13	1,34	0,2377	0,0072	91,74797	91,74797	4,5545	44038	0,00345
S_14	7,24	0,2056	0,0149	31,08189	31,08189	16,6083	16479	0,00527
S_1	22,87	0,1762	0,0146	9,559292	9,558999	25,2957	7907	0,06937
S_2	31,48	0,2214	0,0149	6,657232	6,657232	23,4366	7735	0,08716
S_15	81,81	0,2314	0,0150	2,610679	2,610679	28,7965	4985	0,09108
S_3	84,99	0,2160	0,0149	2,654916	2,654916	26,7567	5538	0,08504
S_16	89,01	0,2644	0,0145	2,339252	2,339252	24,5376	5534	0,10408
S_17	111,64	0,3184	0,0075	2,277092	2,277093	9,0764	9046	0,12534
S_18	141,69	0,2282	0,0146	1,549873	1,549800	32,4655	3920	0,08984
S_19	159,11	0,2728	0,0145	1,345313	1,345314	27,2555	4338	0,10740
S_4	229,88	0,3165	0,0150	1,042821	1,042821	26,3890	4324	0,12460
S_5	250,79	0,3283	0,0147	1,004350	1,004350	24,9764	4470	0,12926
S_20	277,25	0,3257	0,0149	0,896011	0,896010	26,3703	4141	0,12822
S_21	296,64	0,3080	0,0147	0,758910	0,758909	28,5881	3626	0,12125
S_6	297,16	0,2249	0,0145	0,735196	0,735196	36,8574	2860	0,08854
S_22	325,32	0,2370	0,0145	0,682838	0,682837	38,1951	2704	0,09331
S_7	338,92	0,2562	0,0149	0,669246	0,669245	34,8134	3013	0,10087
S_23	412,86	0,3128	0,0075	0,605652	0,605651	12,7634	4643	0,12316
S_24	646,19	0,2597	0,0071	0,179242	0,179242	19,0208	2286	0,10224
S_8	830,34	0,2772	0,0149	0,281422	0,281421	39,9669	2117	0,10913
S_25	856,30	0,2692	0,0152	0,277531	0,277529	42,1445	2022	0,10598

By plotting the results of c and d_c in function of the total calculated pressure dop of the theoretical volume (***Figure 2.***) great correlations were found. Comparing these results with our previous work (Dócs et al., 2018) where only a fraction of this data was at hand (S_1-S_8) the data gained from the newly measured samples shows, that the conclusion made previously for the relations, were false.

By adding the newly measured data the relationship between the pressure difference and both capillary diameter and capillary number can be expressed by a power function rather than an exponential one with good results.

Unfortunately, as in the previous study still no correlations were yet found neither between porosity nor the capillary diameters or the numbers. Needing further investigations to be made.

5. Conclusion

Throughout the investigation of presenting the new method of flow restriction description, the conclusion was made that the major flaw of Darcy's single-phase filtration equation was introducing flow in the total (bulk volume) of the porous material, rather than the pore volume. The implementation of the total cross-sectional area rather than the effective one provides insufficient information on production capacity if no other parameters are provided.

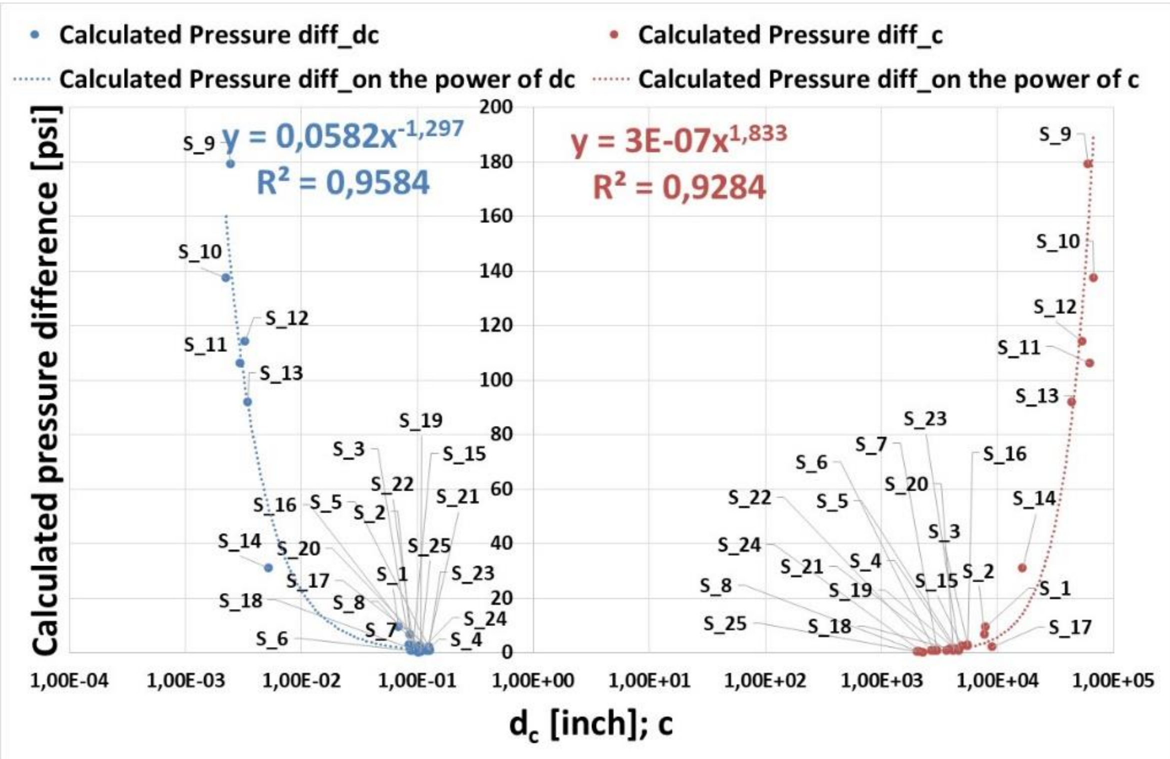

Figure 2. *The c and d_c values in function of pressure loss for all measured samples*

The solution was found where pressure losses were modelled by a theoretical volume equal to the pore volume constructed of multiple steel capillaries of equal diameter. In result presenting a new and more sufficient method of flow restriction modelling in porous materials.

More than twenty measurements were made to verify the newly developed model, in which pressure losses regarding the absolute permeability measurements of sandstone samples (of Hungarian reservoir origin) were observed and used as input data. Throughout the selection process of the samples two criteria were taken into consideration. Primarily all samples were processed from the same geological structure to assure low to no divergence of geologic, sedimentation or diagenetic nature. Furthermore, absolute permeability of the chosen samples required a wide enough range in order to test whether the model had any restrictions.

Results have shown that regarding the tested samples the divergence between calculated and measured pressure losses were infinitesimal, by so proving that the model can represent those restrictions present during the single-phase filtration of incompressible fluid in porous media.

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