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Uncertainty in reservoir rock permeability measurement due to instability in equipment design parameters

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Abstract: Permeability is important reservoir parameters that determine the success of field exploration and production. The decision to produce a field does not only depends on the volume of oil in place but equally on the reservoir permeability. Hence, there is need to obtain accurate permeability value in order to make correct decision on oil well production. Various laboratory experiments being used have repeatability problem. Various experiments were performed over a period of two months to determine the permeability for a sandstone using water as flowing fluid in the Formation Damage System (formation evaluation) equipment and Helium gas as the fluid in the unsteady state Porosimeter-Permeameter. There is so much variation in the values of the permeability obtained and this was discovered to be due to various factors such as the temperature, confining pressure, pore pressure, fluid flowrate and the stability criteria used that have direct impact on measured permeability. It was also discovered that the confining pressure was never stable but changes with the unstable temperature. Maintaining constant temperature was also a problem due to slow heat transfer between the equipment core holder and the flowing or the confining fluid. It was concluded that all these factors that affects permeability need to be accounted for in the permeability measurement and this is only possible if the equipment manufacturers redesign the computer macros used in these computerized permeability systems such that the effect of changing temperature on the confining pressure and the corresponding permeability is corrected. Also considered were the effects of stability criteria and flowrate on the measured permeability values. Correlations were obtained as presented below in the result and discussion section and these are required to be incorporated into the Excel macro used by the equipment manufacturers. For the Porosimeter-Permeameter, a relationship between the absolute permeability, confining pressure, pore pressure, slip velocity and temperature was obtained. For the Formation Damage System, the permeability equation to be used is a little more complex and Macros need to be written based on the different possible flowrates usable with the equipment. Moreover, there is need to have continuous measurement of the confining pressure as it was never constant during the period of experiments.

Keywords: *Permeability, Confining Pressure, Stability Criteria, Permeability Experiment, Equipment repeatability*

Introduction:

Darcy equation relates the rate of fluid flow from the reservoir as directly proportional to the permeability of the reservoir rock and the pressure differential between the reservoir and the well. Porosity, on the other hand, is a measure of the volume of fluid in the reservoir. Accuracy is required in the measurement of the porosity and the permeability for a reservoir rock. Most important measurements for the porosity and permeability is the core analysis.

Core analysis is assumed to be most accurate porosity and permeability measurement since it gives direct measurement of the reservoir properties and serves as a check on the accuracy of other sources of reservoir data such as well logging2.

Faruk[3] states that the correlations of data for gas permeability in tight porous media is a function of the porous media characteristics such as the permeability, porosity, flow tortuosity on the apparent gas permeability, rarefaction coefficient and Klinkenberg gas slippage factor.

Core analysis equipment is manufactured by various equipment manufacturers and calculations are based on pressure differential between two points. Two pressures are involved, confining (overburden) pressure and the pore (back-up) pressure during the laboratory experiments and the two pressure are expected to be constant during the measurement especially at the point of taken the reading. Most common fluid used in the equipment for confining pressure is silicon oil. Unfortunately, the oil is affected by temperature and there is a possibility that the confining pressure will change in the course of a given measurement. Temperature, on the other hand, is difficult to maintain when heating is involved since heat transfer between the heating element and the fluid is mostly non-linear. Every measurement is affected by the equipment sensitivity and so a stability factor is built in to the measurement.

This research studies the effect of confining pressure, stability criteria, flowrate, temperature and duration of experiment on the value of permeability or porosity obtained in laboratory core analysis. Also considered is the slip velocity for gas permeability measurement.

Materials and Methods:

Various core sample were obtained from 2 sources, one was a tight shale and the other a high porous sandstone. This will help to note the sensitivity of the equipment to the easiness of flow.

Major equipment employed initially were, a manual gas Permeameter, manual Porosimeter, computerized Porosimeter - Permeameter and a computerized Formation Damage System (FDS), but only the computerized equipment, which tends to give better results were analyzed further. The computerized Porosimeter - Permeameter and a computerized FDS were later used for the porosity and permeability analysis.

For the FDS, the temperature, flowrate, back pressures and confining pressures were varied and the effects on the permeability were measured. For the Porosimeter-Permeameter, the only factor that is controllable is the confining pressure and it was varied while the effects on the porosity and permeability were measured. Moreover, the equipment has fairly constant temperature.

Results and Discussion:

Present the measurements made in the experiment, compare them with preliminary work or previously published results. In the discussion section you have to relate the results to initial hypotheses.

Table 1 below, presents the absolute permeability and porosity variation with confining pressures and slip velocity for high porous sandstone for the Porosimeter-Permeameter. The measured porosity ranges from 16.384 to 16.581% for confining pressure range of 486.3 to 502psi. The measured permeability ranges from 37.9 to 44.496 for confining pressure range of 492.3 to 513.3psi and a slip velocity of 2.085 to 2.31 m/s.

For low porous shalestone and for the Porosimeter-Permeameter, Table 2 presents variation of absolute permeability and porosity with varying confining pressures and slip velocity. The obtained porosity ranges from 5.004 to 5.064 for a confining pressure range of 477.6 to 527.3 and temperature range of 26.9 to 27.3. The measured absolute permeability ranges from 0.0252 to 0.0272 for a confining pressure grange of 479.5 to 532.7 and slip velocity range of 56.381 to 58.2 m/s.

For the FDS, the measured effective permeability for water varies with confining pressure, back pressure, water flowrate, and duration of experiment and stability criteria as presented in Table 3 and figures 6, 7 and 10. The effective permeability to water obtained varies from 3.4149 to 7.9526mD for a flowarte range of 0.1 to 0.4; confining pressure range of 1060 to 3091psi; back pressure range of 0 to 1407 psi and stability criteria range of 5 to 13%.

The analysis of the results obtained gave the following correlations for the Porosimeter-Permeameter equipment concerning the relationship between the permeability, K, and the confining pressure, the pore pressure, the slip velocity and the time duration of experiment:

$$\ln.P_{conf} = -4980.5\ K + 652.5 \qquad (Eq.1)$$
$$\ln.V_s = -1215.6\ K + 91.175 \qquad (Eq.2)$$
$$\ln T = 1373\ K + 1713.8 \qquad (Eq.3)$$
$$\ln.\ P_p = -46.102\ K + 108.97 \qquad (Eq.4)$$

Where,

K is the absolute permeability, mD
P_{conf} is the confining pressure, psia
T is the temperature, ^oC
P_p is the pore pressure, psia
V_s is the slip velocity, m/s

The plot of semi-log of these parameters and permeability yield a linear relationship as stated in equations 1 to 4 above

The solution to the above four equations gave a relationship for the Porosimeter-Permeameter equipment as follows:

$$K = ln\left[\frac{V_S\ P_p^{1.195}}{T^{18.8}\ P_{conf}^{7.195}}\right]^{20.374} \qquad (Eq.\ 5)$$

.For the FDS, the following were obtained:

$$P_{conf} = 290.05.K_{eff}^{1.1622}\ \text{(flowrate of } 0.1\,{}^m/_s)$$
$$P_{conf} = 1194.1\ K_{eff}^{0.4303}\ \text{(flowrate of } 0.\ 2\,{}^m/_s) \qquad (Eq.6)$$

It was discovered that apart from the above, the stability criteria (SC) also affect the measured effective permeability such that the K_{eff} and the SC can be compared with a complex relationship as follows:

$$K_{eff} = -0.0247\ SC^4 + 0.9255\ SC^3 - 12.552\ Sc^2 + 72.225\ SC - 140.79 \qquad (Eq.5)$$

where SC is the stability criteria at flowrate of 0.2m/s.

Conclusion:

The measured permeability increases with increasing flowrate which is in agreement with the Darcy law when pressure drop is constant. Though the permeability values obtained has a standard deviation of 0.0371%, which is acceptable, unfortunately the requirement of petroleum industry is a single permeability value at a given pressure drop down. Hence, the excel macro used by these equipment needs to be redesigned so that a given permeability value is obtained no matter the flowrate used. This is possible by incorporating the various parameters that affects the permeability. Incorporating the logarithm relationship on equation 1 to 4 above gave a single permeability value for a core sample when the unsteady state Porosimeter-Permeameter is used as shown in equation 5 above.

The FDS equipment required that the relationship between confining pressure and permeability be evaluated for all possible flowrates, back pressures and stability criteria and different Excel Macro be used to analyze the obtained permeability value at the selected flowrate. Equation 5 correlate the stability criteria to the permeability measured at 0.2m/s flowrate and a back pressure of 891psi.

References:

[1] Darcy, H. (1856). "Les Fontaines Publiques de la Ville de Dijon", Dalmont, Paris.

[2] Emad A Eysa et al (2016), "Reservoir Characterization using porosity-permeability relations and statistical analysis: a case study from North Western Desert, Egypt", Arabian Journal of Geosciences,. p.9:403

[3] Faruk Civan (2010), "Effective Correlation of Apparent Gas Permeability in Tight Porous Media", Transport in Porous Media, March 2010, Volume 82, Issue 2, pp 375-384

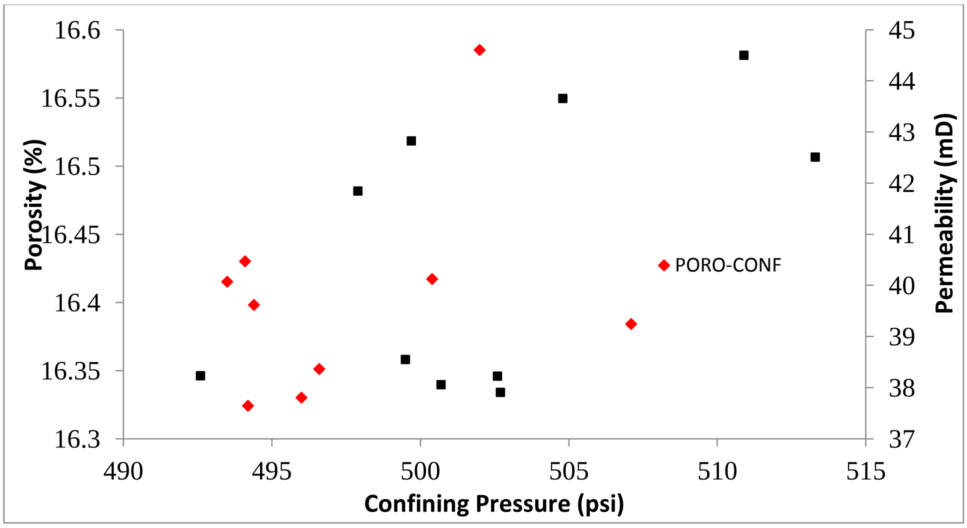

Figure 1: Porosity and Gas Permeability Variation With Confining Pressure For High Porous Sandstone

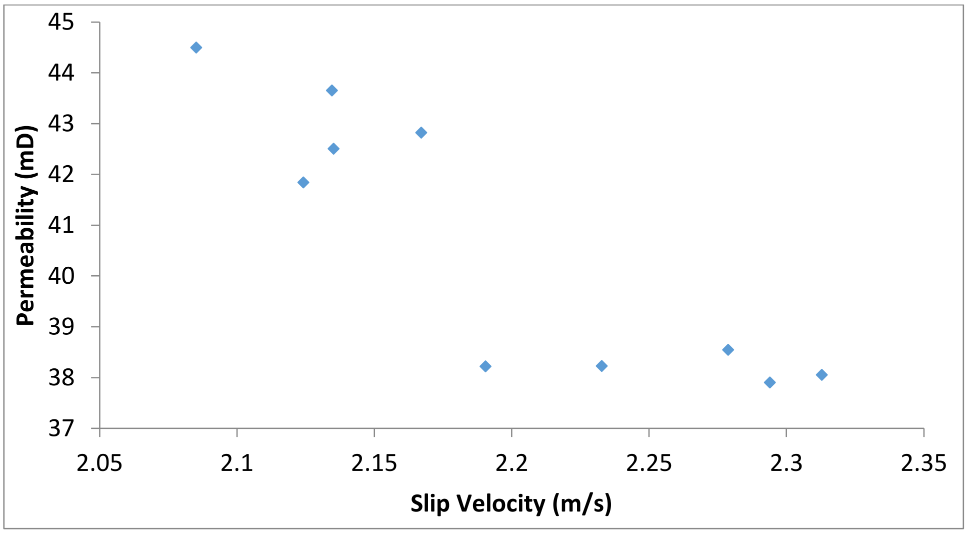

Figure 2: Gas Permeability Variation With Slip Velocity For High Porous Sandstone

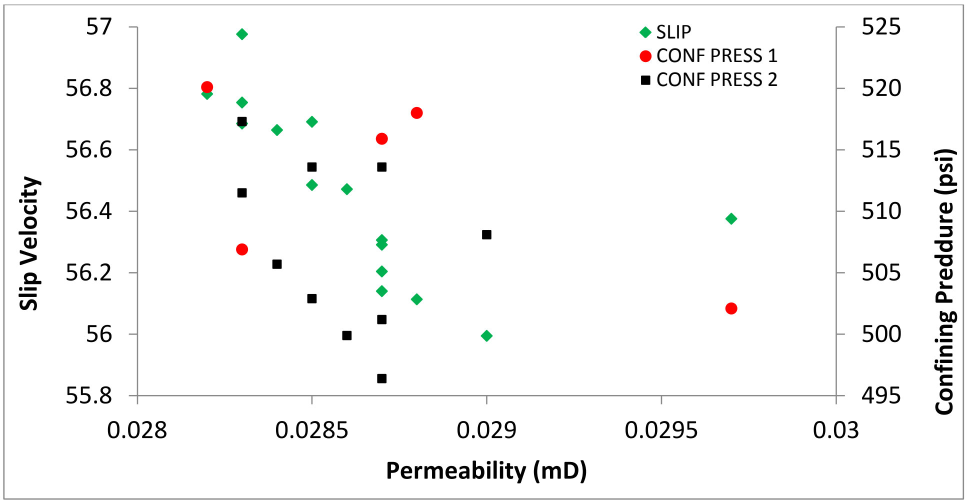

Figure 3: Gas Permeability variation With Confining Pressure and Slip Velocity For Low Porosity Shalestone

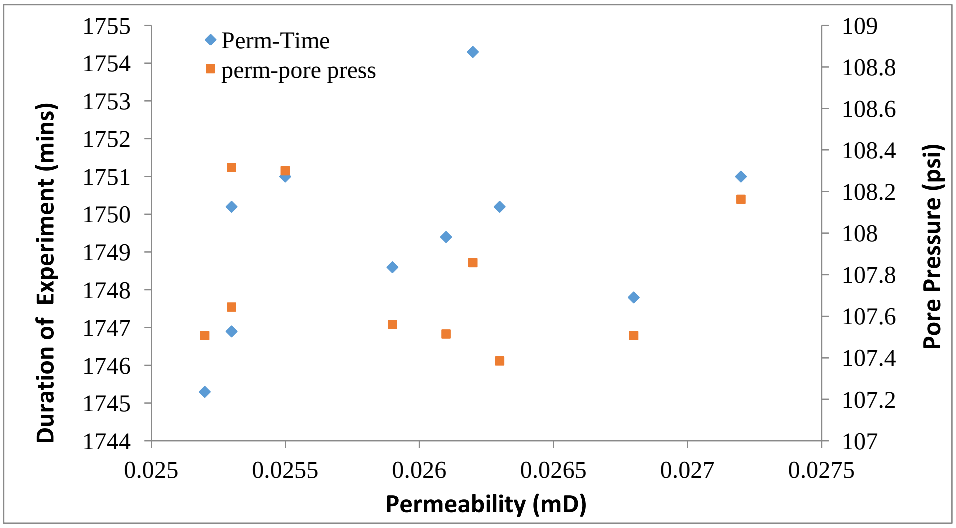

Figure 4: Gas Permeability Variation With Duration of Experiment and Pore Pressure For Low Porosity Shalestone

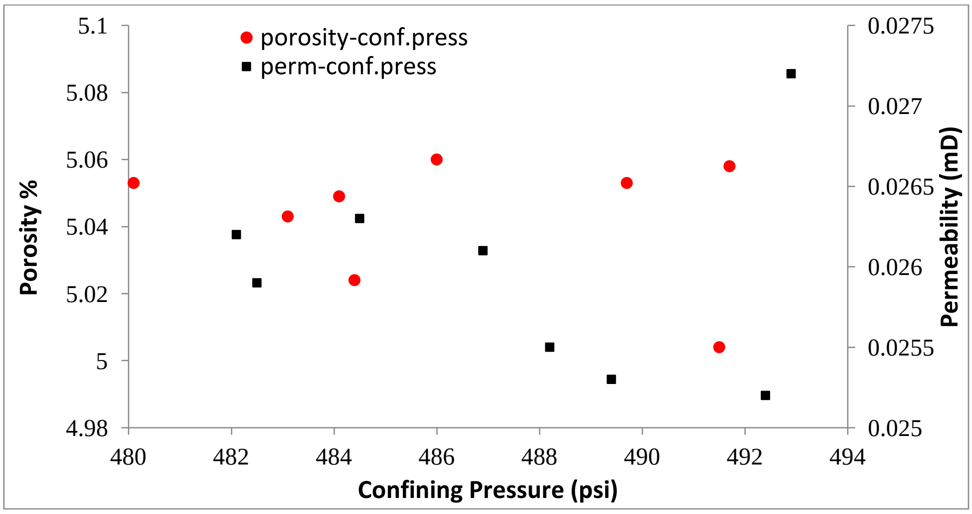

Figure 5: Porosity - Gas Permeability variation With Confining Pressure For Low Porous Shalestone (Long Flow Regime)

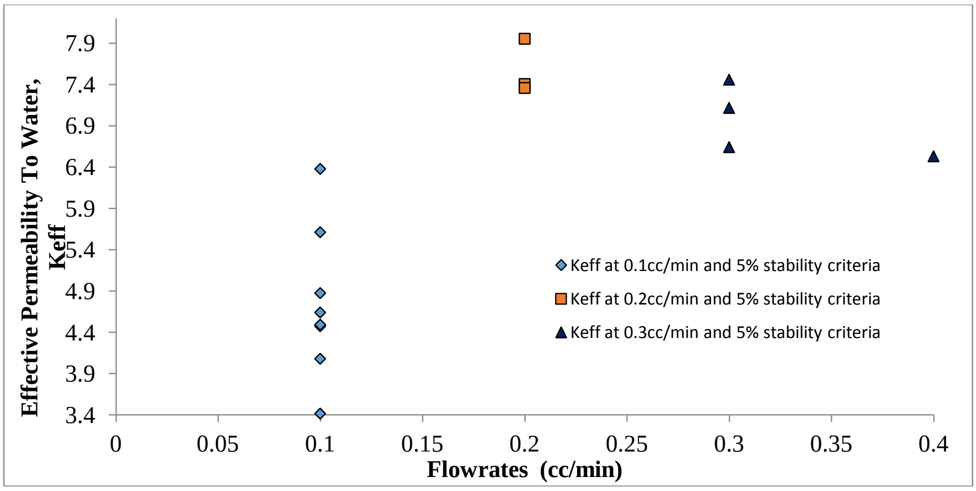

Figure 6: Effective Permeability To Water At various Flowrates For High Porosity Sandstone for the FDS

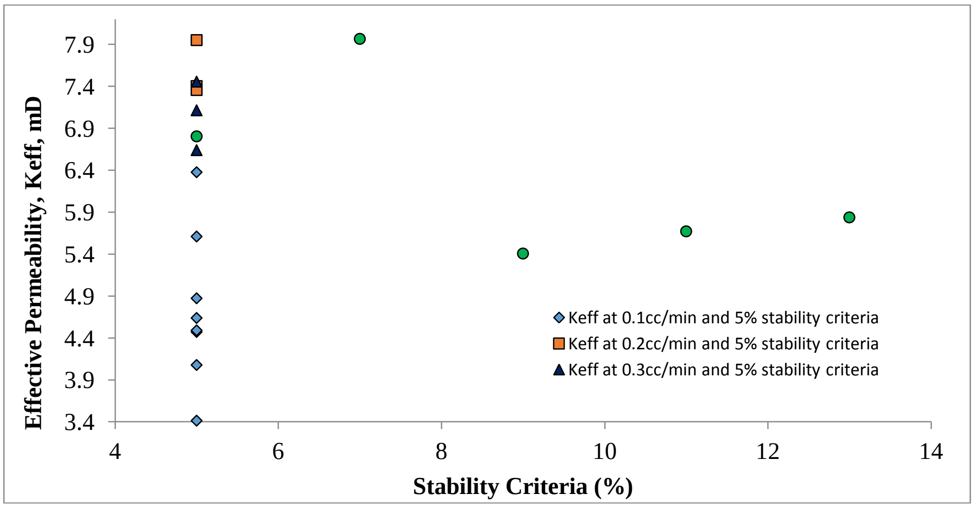

Figure 7: Effective Permeability To Water At Varying Stability Criteria For High Porosity Sandstone for the FDS

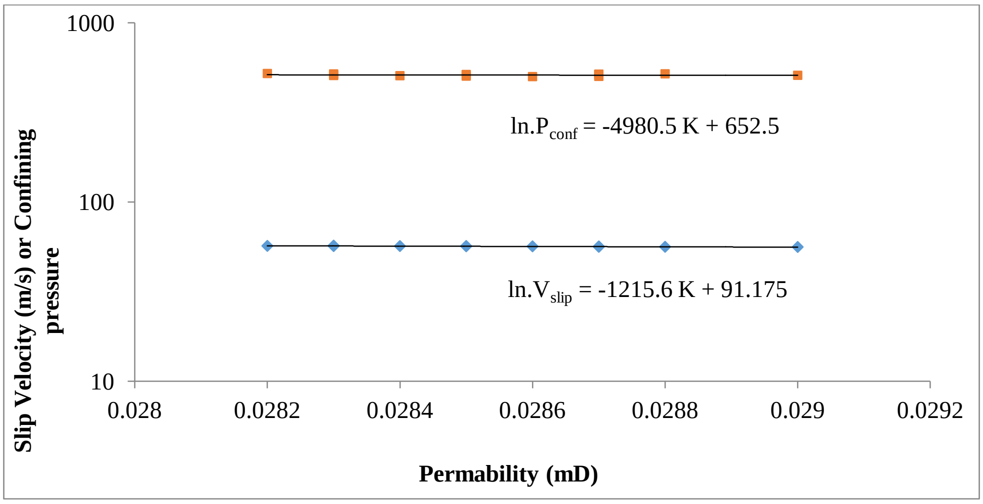

Figure 8: Linearized Confining Pressure and Slip Velocity Variation With Permeability For Low Porous Shalestone

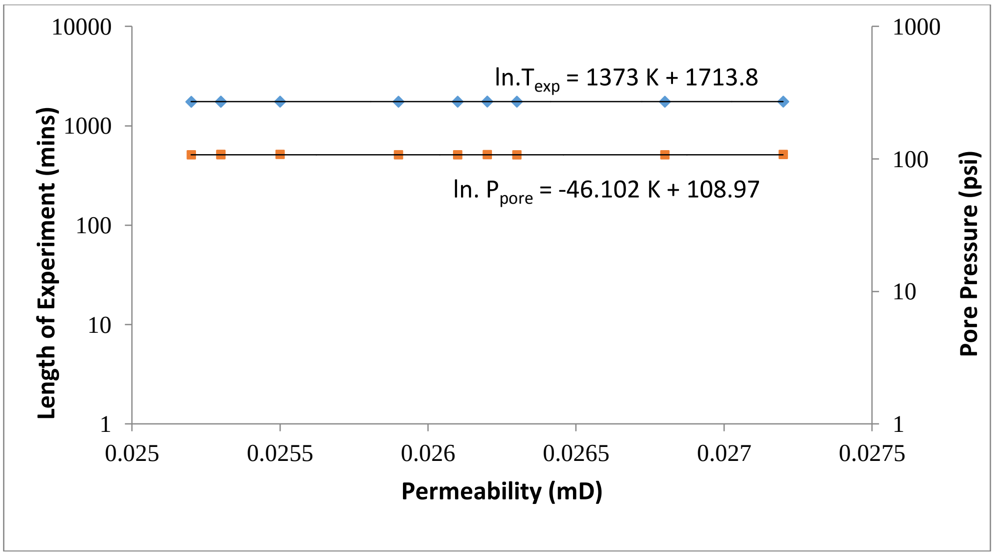

Figure 9: Linearized Duration of Experiment and Pore Pressure Variation With Permeability

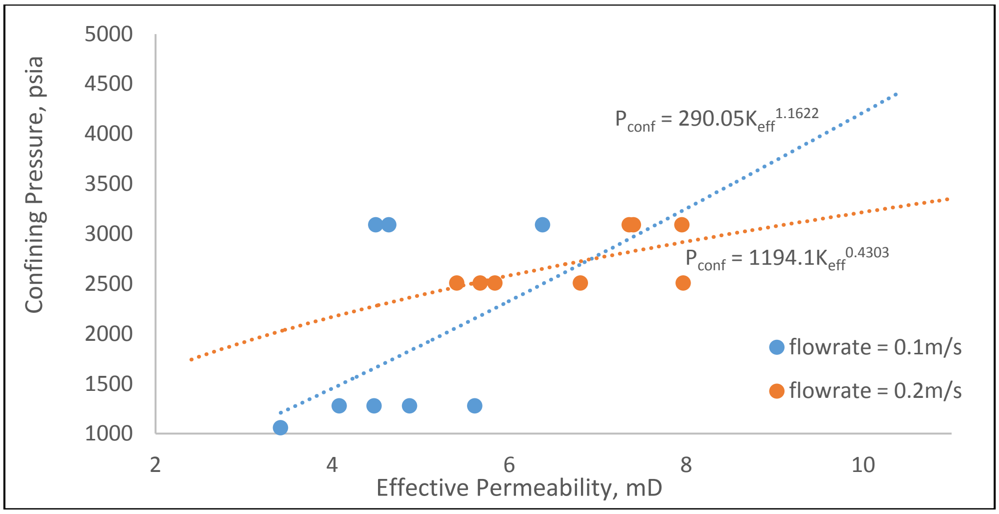

Figure 10: Effective Permeability-confining Pressure relationship at Different Flowrates for FDS

Table 2: Permeability, Porosity, Confining Pressures and Slip Velocity For High Porous Sandstone Using Computerized Porosity - Permeameter

Porosity (%)	Confining Pressure (psi)	Temp (oC)	Absolute Permeability (mD)	Confining Pressure (psi)	Slip Velocity (m/s)
16.585	502	26.3	44.4963	510.9	2.0852
16.417	500.4	26.3	43.6521	504.8	2.1346
16.398	494.4	26.3	42.8217	499.7	2.1671
16.384	507.1	26.5	42.5052	513.3	2.1352
16.43	494.1	26.4	38.547	499.5	2.2788
16.351	496.6	26.4	38.2213	502.6	2.1905
16.33	496	26.4	37.9037	502.7	2.294
16.324	494.2	26.4	38.0539	500.7	2.3129
16.352	486.3	26.5	38.2287	492.6	2.2328
16.415	493.5	26.5	41.8416	497.9	2.1242

Table 3: Permeability, Porosity, Confining Pressures and Slip Velocity For Low Porous Shalestone Using Computerized Porosity - Permeameter

Porosity (%)	Confining Pressure (psi)	Temp (oC)	Absolute Permeability (mD)	Confining Pressure (psi)	Slip Velocity (m/s)
5.058	491.7	27.1	0.0272	492.9	56.8117
5.064	527.3	27.9	0.0253	532.7	58.3043
5.053	489.7	27.2	0.0255	488.2	57.8196
5.004	491.5	27.2	0.0252	492.4	58.2062
5.06	486	27.1	0.0253	489.4	58.0879
5.049	484.1	27.1	0.0261	486.9	57.0185
5.053	480.1	27.1	0.0262	482.1	56.5602
5.037	477.6	26.9	0.0268	479.5	56.3583
5.024	484.4	27	0.0263	484.5	56.3808
5.043	483.1	27.1	0.0259	482.5	56.8423

Table 4: Permeability Variation With Confining Pressure and Slip Velocity For Low Porous Shalestone 2

Porosity (%)	Confining Pressure (psi)	Temp (oC)	Absolute Permeability (mD)	Confining Pressure (psi)	Slip Velocity (m/s)
6.009	517.6	26.9	0.0282	520.1	56.7818
			0.0283	506.9	56.9761
			0.0287	515.9	56.1403
			0.0288	518	56.1137
			0.0283	517.3	56.6854
			0.0283	511.5	56.7539
			0.0285	513.6	56.4856
			0.0287	513.6	56.2044
			0.029	508.1	55.9949
			0.0284	505.7	56.6643
			0.0286	499.9	56.472
			0.0285	502.9	56.6911
			0.0287	501.2	56.2913
			0.0287	496.4	56.3065

Table 5: Permeability To Water, Flowrate and Stability Criteria Using computerized Formation Damage System For High Porous Sandstone.

Quantity injected (cc)	Flowrate (cc.min-1)	Duration of step (min)	Stability criterion (%)	Effective Permeability Keff (mD)	Confining Pressure. (psi)	Back Pressure. (psi)	Temp. (°C)
4	0.1	40	5	3.4149	1060	0	26.5
4	0.1	40	5	5.6109	1279	1069	42.6
4	0.1	40	5	4.8739	1279	1069	42.6
4	0.1	40	5	4.4726	1279	1069	42.6
4	0.1	40	5	4.0786	1279	1069	42.6
2	0.2	10	5	6.8049	2508	891	42.8
2	0.2	10	7	7.9674	2508	891	42.8
2	0.2	10	9	5.4076	2508	891	42.8
2	0.2	10	11	5.6722	2508	891	42.8
2	0.2	10	13	5.8387	2508	891	42.8
3	0.1	30	5	4.4914	3091	1407	38.2
3	0.1	30	5	4.6391	3091	1407	38.2
3	0.1	30	5	6.3773	3091	1407	38.2
4	0.2	20	5	7.4046	3091	1407	38.2
4	0.2	20	5	7.9526	3091	1407	38.2
4	0.2	20	5	7.3572	3091	1407	38.2
6	0.3	20	5	6.6404	3091	1407	38.2
6	0.3	20	5	7.4575	3091	1407	38.2
6	0.3	20	5	7.1157	3091	1407	38.2
8	0.4	20	5	6.5298	3091	1407	38.2