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**An Experimental and Theoretical Study to Relate
Uncommon Rock/Fluid Properties to Oil Recovery**

QUARTERLY REPORT FOR THE PERIOD

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RESEARCH SUMMARY

TITLE: An Experimental and Theoretical Study to Relate
Uncommon Rock/Fluid Properties to Oil Recovery

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MAJOR ACHIEVEMENTS

The major objective of the current quarter is to develop new empirical mercury recovery efficiency and permeability correlations to improve the accuracy of estimating behavior of fluid flow through various layers of limestone reservoir rocks. The correlations

References and Illustrations at the end of paper.

are to be developed from 329 experimentally obtained mercury porosimetry properties data.

OVERALL PROJECT OBJECTIVES

The overall objectives of the project are:

- To develop a better understanding of some important but not really well investigated rock/pore properties such as: tortuosity, pore-size distribution, surface area, and wettability, and a better insight on capillary pressure variation with respect to wettability and pore geometry of sandstone and limestone.
- To improve the understanding of fluid flow in porous media under conditions of secondary and tertiary recovery, through the laboratory study of the performance of enhanced recovery methods such as waterflooding.
- To develop empirical relationships between residual oil saturation and oil recovery at breakthrough and the uncommon rock/pore properties. Develop relationships between residual oil saturation and ultimate oil recovery at floodout and the uncommon rock/pore properties for the different porous media. Furthermore, variations of irreducible water saturation, porosity and absolute permeability with respect to the uncommon rock/pore properties, residual oil saturation and oil recovery will be investigated.

ACTUAL WORK-PREVIOUS QUARTER

During the previous quarter, new correlations for estimating sandstones mercury recovery efficiency and permeability values were developed. The correlations were developed from 450 experimentally obtained mercury porosimetry data.

WORK PLANNED-CURRENT QUARTER

Plans for the current quarter consist of the following:

- Develop new correlations for estimating mercury recovery efficiency values for limestones.
- Develop new correlations for estimating permeability values for limestones using mercury porosimetry measured data.

ACTUAL WORK-CURRENT QUARTER

During the current quarter, new empirical mercury recovery efficiency and permeability correlations for limestones were developed. The correlations were developed by utilizing the 329 core-plugs data that were previously obtained from the mercury porosimetry analyses for limestones.

INTRODUCTION

The estimation of the behavior from mercury porosimetry properties data is important when routine measurements cannot be performed, as in the case of very small core plugs or drill-cuttings. The estimation is also important when there is need to minimize core analysis cost or when the measurements of the behavior are of questionable accuracy, as in the case of reservoir rocks with microfractures.

RESULTS AND DISCUSSION

Mercury Recovery Efficiency Correlation for Limestones

Using non-linear multiple regression analysis, a new correlation for estimating mercury recovery efficiency values for limestones is developed from 329 experimentally obtained mercury porosimetry data. It was initially assumed that:

$$RE = f (V_{int.}, SA, S_s, D, \rho_s, \phi_{Hg}) \quad (1)$$

After a series of analyses using the best subset algorithms, which is available in MINITAB statistical computer package (Ryan et al., 1985), it was observed that specific surface area could be removed from the list of independent variables in Eq. 1. The equation can then be re-written as:

$$RE = f (V_{int.}, SA, D, \rho_s, \phi_{Hg}) \quad (2)$$

Again, with further modification, Eq. 2 is assumed to be of the general form:

$$RE = \frac{SA^E \phi_{Hg}^F}{A V_{int.}^B D^C \rho_s^D} \quad (3)$$

In Eq. 3, A, B, C, D, E, and F are coefficients of the correlation. By regressing the available mercury porosimetry data obtained from 329 Indiana limestone core plug samples, the values of the coefficients were obtained. After the substitution of the values of the coefficients into Eq. 3, it results into the new correlation for estimating mercury recovery efficiency for limestones, as presented in Eq. 4:

$$RE = \frac{SA^{0.188} \phi_{Hg}}{3.53 V_{int.}^{1.13} D^{0.262} \rho_s^{1.20}} \quad (4)$$

The units of mercury recovery efficiency, RE, mercury porosity, ϕ_{Hg} , and the other variables in Eq. 4 are as defined in the nomenclature.

To test how good the correlation is, a crossplot to compare the predicted mercury recovery efficiency values using Eq. 4 with the measured values is shown in Fig. 1. Most of the plotted data points of this new correlation fall close to the 45° line, indicating its good degree of correlation. This new correlation has a standard deviation of 0.052, F-test statistic value of 375.0, and statistically significant with p-value of 0.000.

The plotted residuals versus measured mercury recovery efficiency for limestones is shown in Fig. 2. The trend of the scatter data points shows a directly increasing relation. The behavior of the plot suggests the addition of another independent variable to the correlation. One observation that can be drawn from this, is that an additional contribution to the dependent variable, mercury recovery efficiency, may be made by some property of the pore structure which was not measured in this study.

The predictive strength of the new correlation (Eq. 4) for estimating mercury recovery efficiency of limestones was compared with the correlation presented by Al-Fossail et al. (1991). The correlation by Al-Fossail et al. was developed using Saudi Arabian carbonate reservoir rocks. The correlation is given in Eq. 5 below:

$$RE = 16.876 + 1.4075 \phi_{Hg} \quad (5)$$

In Eq. 5, mercury recovery efficiency, RE, and mercury porosity, ϕ_{Hg} , are both expressed as percentages.

The crossplot for comparing the predicted mercury recovery efficiency values using Eq. 5 with the measured values is shown in Fig. 3. Unlike the case of the new correlation, most of the plotted data points of Al-Fossail et al. correlation scatter widely along both sides of the 45° line, indicating that this correlation is not as good as the new correlation.

This conclusion is further strengthened by the plot of Al-Fossail et al. correlation's residuals versus measured mercury recovery efficiency, which is shown in Fig. 4. The trend of the scatter data points is more directly related than that of Fig. 2. The behavior of this plot suggests the addition of more independent variables to the Al-Fossail et al. correlation, before its predictive capability could be improved.

Permeability Correlation for Limestones

The permeability dictates the speed at which fluid flow through various layers of reservoir rock (Pugh et al., 1991). There is an increasing need for good, simple to use correlation to estimate permeability. The estimation of reservoir rock permeability from mercury porosimetry data is important when routine permeability measurements cannot be performed, as in the case of very small core plugs or drill-cuttings. This estimate is also important when there is a need to minimize core analysis cost or when measurements of permeability are of questionable accuracy, as in the case of reservoir rocks with microfractures.

Using non-linear multiple regression analysis, as in the case of mercury recovery efficiency, a new correlation for estimating permeability values for limestones using coreflood or mercury porosimetry measured data has been developed. The development was initiated using the 16 limestone cores waterflood and mercury porosimetry experimentally obtained data. Here, it was initially assumed that:

$$k = f (\phi , V_{int.} , SA , S_s , D , \rho_s) \quad (6)$$

The primary reason for using only the initial independent variables contained in Eq. 6, was to develop a correlation to estimate permeability based on the rock properties determined using mercury porosimetry.

In Eq. 6, the independent variable, ϕ , can either be brine porosity or mercury porosity, depending on whether the permeability is to be estimated from waterflood experimental core data (brine permeability) or from mercury porosimetry experimental core plug data (mercury permeability). After a series of analyses, it was observed that permeability could be correlated with only porosity, surface area, and specific surface area as the independent variables in Eq. 6. The equation can then be re-written as:

$$k = f(\phi, SA, S_s) \quad (7)$$

To further improve the correlation, Eq. 7 was modified by dividing the dependent variable by $(1-\phi)^2$, which implies that:

$$\frac{k}{(1-\phi)^2} = f(\phi, SA, S_s) \quad (8)$$

After applying multiple regression analysis methods on Eq. 8, the resulting developed correlation for estimating permeability is given as:

$$k = \frac{3.146 * 10^3 \phi^{2.98}}{SA^{0.0234} S_s^{0.0185} (1-\phi)^2} \quad (9)$$

In Eq. 9, permeability, k , is expressed in millidarcy and porosity, ϕ , is expressed as fraction. The other variables in the equation are as defined in the nomenclature.

To show how good the correlation is, a crossplot to compare the predicted brine permeability values using the new correlation, as presented in Eq. 9, with the measured values is shown in Fig. 5. The plotted data points deviate from the 45° line and not as good as would have been expected. Part of the scatter in the crossplot between predicted brine permeability and measured brine permeability may be artificial, caused by the inclusion of measurements from plugs with induced fractures, which were not easily

noticeable by visual inspection of the plugs. The new correlation is statistically significant at $\alpha = 0.001$ level. The plotted residuals versus measured brine permeability values for limestones is shown in Fig. 6. The behavior of the plot suggests that porosity, surface area, and specific surface area were enough to develop a good correlation for permeability.

The predictive strength of the new correlation (Eq. 9) for estimating permeability of limestones was compared with the correlation presented in the study by Wang et al. (1991). The laboratory measured data obtained for this study were used for the comparison, due to the non-availability of independently measured data sets. The correlation by Wang et al. was developed using laboratory measured samples of 54 carbonates cores from 11 oil-producing reservoirs. The correlation is given in Eq. 10 below:

$$\ln k = 29.0585 \phi - 1.6348 \quad (10)$$

In Eq. 10, permeability, k , is in millidarcy and porosity, ϕ , is expressed as fraction.

The crossplot to compare the predicted permeability values using Eq. 10 with the measured values is shown in Fig. 7. Unlike the case of the new correlation, most of the plotted data points of Wang et al. correlation scatter widely along the upper part of the 45° line, indicating that this correlation mostly over-predicts. This conclusion is further strengthened by the plot of Wang et al. correlation's residuals versus measured permeability, which is shown in Fig. 8. The behavior of the scatter data points shows that it over-predicts and not as good as the scatter plots of Fig. 6. The behavior of the plot suggests the addition of more independent variables to the correlation of Wang et al., before its predictive capability could be improved.

Equation 9 was also used to estimate mercury permeability of the core plug samples. The resulting estimates of mercury permeability values for the 329 limestone core plug samples were plotted against the respective values of their measured mercury porosity

values, as shown in Fig. 9. Again, similar to the sandstone case, the plotted data points fall very close to an exponential trend as expected for the relationship of porosity with permeability. Finally, the estimated average mercury permeability values were compared with the measured brine permeability values as shown in Fig. 10. The comparison was good, but could to be better improved.

PROBLEMS ENCOUNTERED

No technical problems were encountered.

WORK PLANNED-NEXT QUARTER

Plans for the next quarter consist of the following:

- Develop new correlations for estimating residual oil saturation values at breakthrough for sandstones.
- Develop new correlations for estimating residual oil saturation values at floodout for sandstones.
- Develop new correlations for estimating oil recovery values at breakthrough for sandstones.
- Develop new correlations for estimating ultimate oil recovery values at floodout for sandstones.
- Validate the developed models.

CONCLUSIONS

The following conclusions are deduced from this study:

- New empirical correlations that can be easily programmed for computer application have been developed to estimate mercury recovery efficiency and permeability for limestones. The permeability correlations can also be employed as a tool to estimate mercury porosimetry derived permeability values.
- It was shown that besides porosity, total mercury intrusion volume, pore surface area, average pore diameter and apparent (skeletal) density are important factors for mercury recovery efficiency estimations. Further, besides porosity, pore surface area and specific surface area are important factors for permeability estimations.

NOMENCLATURE

—		
D	=	average pore diameter (micrometer)
f	=	function of
F	=	statistical F-test
k	=	permeability (md)
p-value	=	significance level
RE	=	mercury recovery efficiency (fraction)
SA	=	total Pore Area (or surface area) (sq. m/g)
S_s	=	specific surface area (cm^2/cm^3)
$V_{\text{int.}}$	=	total intrusion volume (or pore volume) (ml/g)

ρ_s	=	apparent (skeletal) density (g/ml)
ϕ	=	porosity (fraction)
ϕ_{Hg}	=	mercury porosimetry measured porosity (fraction)

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