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

AUG 05 1993

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QUARTERLY REPORT FOR THE PERIOD

January 1, 1993 Through March 31, 1993

Prepared by
Robert W. Watson, Turgay Ertekin and Olubunmi O. Owolabi

The Pennsylvania State University
College of Earth & Mineral Sciences
Mineral Engineering Department
Petroleum & Natural Gas Engineering Section
102 Mineral Sciences Building
University Park, PA 16802

Prepared for
U.S. Department of Energy
Bartlesville Project Office
Under Contract No. DE-AC22-89BC14477

DOE Project Manager
Gene Pauling

US/DOE patent clearance is not required prior to the
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RESEARCH SUMMARY

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

CONTRACT: DE-AC22-89BC14477

CONTRACTOR: The Pennsylvania State University
Vice President for Research
114 Kern Building
University Park, PA 16802

Administrative Officer: David A. Shirley

PRINCIPAL INVESTIGATOR: Robert W. Watson
Assistant Professor
Petroleum and Natural Gas Engineering
102 Mineral Sciences Building
University Park, PA 16802

REPORTING PERIOD: January 1, 1993-March 31, 1993

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 sandstone reservoir rocks. The correlations

References and Illustrations at the end of paper.

are to be developed from 450 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, mercury porosimetry experiments were completed on 16 Indiana limestone linear cores and 512 core plugs. The porosimetry properties obtained were fully analyzed and related to the previously obtained petrophysical, waterflood, and wettability properties.

WORK PLANNED-CURRENT QUARTER

Plans for the current quarter consist of the following:

- Develop new correlations for estimating mercury recovery efficiency values for sandstones and limestones.
- Develop new correlations for estimating permeability values for sandstones and limestones using mercury porosimetry measured data.
- Experimentally and statistically describe all the independent variables from waterflood, wettability and mercury porosimetry experiments to residual oil saturation and oil recovery, for limestones.

ACTUAL WORK-CURRENT QUARTER

During the current quarter, new empirical mercury recovery efficiency and permeability correlations for sandstones were developed. The correlations were developed by utilizing the 450 core-plugs data that were previously obtained from the mercury porosimetry analyses for sandstones.

INTRODUCTION

Adequate estimation of the field behavior during primary and enhanced recovery period requires representative laboratory measurements. Moreover, 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 Sandstones

Adequate prediction of the field behavior during primary or enhanced recovery period requires representative laboratory measurements. Using non-linear multiple regression analysis, the correlation for estimating mercury recovery efficiency values for sandstones is developed from 450 experimentally obtained mercury porosimetry data. It was initially assumed that:

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

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:

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

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

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

In Eq. 3, A, B, C, D, E, and F are coefficients of the correlation. By regressing the available mercury porosimetry data obtained from 450 Berea sandstone 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 sandstones, as presented in Eq. 4:

$$RE = \frac{SA^{0.689} \phi_{Hg}}{26.9 V_{int}^{1.65} \bar{D}^{0.242} \rho_s^{0.369}} \quad (4)$$

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 the quality of the correlation, a crossplot to compare the predicted mercury recovery efficiency values using Eq. 4 with the measured values is shown in Fig. 1. The solid 45° line in the figure represents a perfect correlation between the measured and estimated mercury recovery efficiencies. Most of the plotted data points of this new correlation fall close to the 45° line, indicating its good degree of correlation. It has a standard deviation value of 0.0569, F-test statistic value of 232.0, and statistically significant with p-value of 0.000.

Furthermore, another method of evaluating the adequacy of the regressed correlation is to examine a plot of the residuals, which are simply the differences between the individual measured values of the dependent variable and the predicted values. This plot of residuals versus measured mercury recovery efficiency for sandstones is shown in Fig. 2. The behavior of the plot suggests that the independent variables in the correlation were enough to define the dependent variable.

Permeability Correlation for Sandstones

The permeability dictates the speed at which fluid flow through various layers of reservoir rock (Pugh et al., 1990). 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 sandstones using coreflood or mercury porosimetry measured data has been developed. The development was initiated using the 21 sandstone cores waterflood and mercury porosimetry experimentally obtained data. Here, it was initially assumed that:

$$k = f(\phi, V_{int}, SA, S_s, \bar{D}, \rho_s) \quad (5)$$

The primary reason for using only the initial independent variables contained in Eq. 5, was to develop a correlation to estimate permeability based on the rock properties determined using mercury porosimetry.

In Eq. 5, 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. 5. The equation can then be re-written as:

$$k = f(\phi, SA, S_s) \quad (6)$$

To further improve the correlation, Eq. 6 was modified by dividing the dependent variable by $(1-\phi)^2$, which implies that:

$$\frac{k}{(1-\phi)^2} = f(\phi, SA, S_s) \quad (7)$$

After applying multiple regression analysis methods on Eq. 7, the resulting developed correlation for estimating permeability is given as:

$$k = \frac{7.834 * 10^5 \phi^{3.46} (1 - \phi)^2 SA^{0.230}}{S_s^{0.192}} \quad (8)$$

In Eq. 8, permeability, k , is expressed in millidarcy and porosity, ϕ , is expressed in 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. 8, with the measured values is shown in Fig. 3. Most of the plotted data points of this new correlation fall close to the 45° line, indicating its a good correlation. It has a standard deviation of 0.0546, F-test statistic value of 191.3, and statistically significant at $\alpha = 0.001$ level. The plotted residuals versus measured brine permeability values for sandstones is shown in Fig. 4. The behavior of the plot suggests that porosity, surface area, and specific surface area were enough to develop a good correlation for permeability.

Equation 8 was also used to estimate mercury permeability of the core plug samples. The resulting estimates of mercury permeability values for the 450 sandstone core plug samples were plotted against the respective values of their measured mercury porosity values, as shown in Fig. 5. The plotted data points fall very close to an exponential trend as expected for the relationship of porosity with permeability.

Swanson (1981) developed permeability correlations for sandstones and carbonates using parameters from capillary-pressure curves. His data base consists of 116 carbonates and 203 sandstones from 74 formations. Thompson et al. (1987) used percolation theory to develop theoretical models to predict permeability from mercury porosimetry data. They proposed that the theory was valid for essentially all porous rocks. Other recent

permeability correlations include those of Pittman (1992) and Kamath (1992). The predictive strength of the new correlation for sandstones is not compared with that of these correlations. This was because the conductivity formation factor values for the rock samples needed to use Thompson et al.'s model, were not measured in this study. Also, it is time consuming to estimate the values of the maximum of the parameter, S_{Hg}/P_c , needed to be able to use the various models developed by Swanson, Pittman, and Kamath.

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

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 sandstones. 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

$\bar{D}$	=	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)
$V_{int.}$	=	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)

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support of the U.S. Department of Energy to the Pennsylvania State University through Contract No. DE-AC22-89BC14477.

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Fig. 1: Comparison of Measured Mercury Recovery Efficiency Values for Sandstones with those Predicted by the New Correlation.

Fig. 2: Plotted Residuals Using the New Correlation vs. Measured Mercury Recovery Efficiency for Sandstones.

Fig. 3: Comparison of Measured Permeability Values for Sandstones with those Predicted by the New Correlation.

Fig. 4: Plotted Residuals Using the New Correlation vs. Measured Permeability for Sandstones.

Fig. 5: Mercury Permeability for Sandstones Predicted by Using the New Correlation vs. Measured Mercury Porosity.

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