A Viscosity Correlation for Gas-Saturated Crude Oils

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ABSTRACT

A correlation is presented for predicting the viscosity of gas-saturated crude oils under reservoir conditions. It is based on the dead oil viscosity and the solution GOR. The correlation was developed from a study which showed that at a fixed solution GOR, the relation between the gas-saturated oil viscosities and the corresponding dead oil viscosities is a straight line on logarithmic coordinates.

Data from 457 crude oil samples from the major producing areas of the U. S., Canada and South America were used. The best straight lines through the data were fitted by the method of least squares with a digital computer. The correlation is presented in the form of an equation and also in a convenient graphical form.

INTRODUCTION

The viscosity of gas-saturated crude oils under reservoir conditions is an important physical property used in reservoir engineering calculations. Many difficulties are inherent in the sampling of gas-saturated oils and in the laboratory measurement of their viscosities. Therefore, it is frequently neither possible nor convenient to obtain measured values, so the viscosity must be estimated from other, more readily available data.

This paper presents a correlation for predicting the viscosity of gas-saturated crude oils. The correlation is based on the amount of gas in solution and the viscosity of the dead oil at the temperature of interest.

A previous correlation of these variables was presented by Beal[1]. In comparison, the correlation presented here extends to a higher GOR and to a lower dead oil viscosity. Over the range of variables covered by both, this correlation is based on approximately 11 times as many oil samples.

DEVELOPMENT OF CORRELATION

A study was made of the variables or parameters which could be used to relate the viscosity of a gas-saturated oil to its dead oil viscosity. Preference was given to those variables which are easily and commonly measured in the field or in the laboratory. It was found that either the differential liquid formation volume factor or the solution GOR of the gas-saturated oil could be used as a correlating parameter. The solution GOR was selected for the correlation because of its simplicity and availability.

In an attempt to refine the correlation by introducing a second parameter, the following additional variables were tested: differential liquid formation volume factor at the reservoir bubble point, the formation volume factor at the saturation pressure for the GOR of interest, reservoir temperature, viscosity of C_7^+ fraction at 100°F and atmospheric pressure, weighted average gravity of gas in solution, oil gravity, reservoir bubble point pressure, saturation pressure at the selected GOR and reservoir temperature, and gas mol fraction. None of these improved the correlation to any significant extent.

It was found that at any fixed solution GOR, the relation between the gas-saturated oil viscosities and the corresponding dead oil viscosities is a straight line on logarithmic coordinates, for the range of variables investigated. This straight-line relationship was used for the correlation.

Viscosity data on a total of 457 crude oil samples were used. The data were obtained with rolling ball-type viscometers. The samples came from all of the important producing areas of the U. S., as well as from Canada and South America. Their geographical distribution is shown in Table 1. The ranges of properties represented by these samples are as follows:

Property	Range of Values Minimum	Maximum	Weighted average
Reservoir temperature, °F	72	292	146
Reservoir bubble point pressure, psia	132	5,645	1,694
Solution GOR at reservoir bubble point, cu ft/bbl	51	3,544	590

For each crude oil sample the viscosity of the liquid phase from each step of a differential liberation was plotted against its solution GOR on semi-logarithmic paper. A smooth curve was drawn through the points and values of viscosity in centipoises were read from

TABLE 1—GEOGRAPHICAL DISTRIBUTION OF OIL SAMPLES USED IN CORRELATION

Field location	Number of samples
Arkansas	1
California	33
Canada	3
Colorado	2
Kansas	7
Louisiana	24
New Mexico	27
Oklahoma	39
South America	17
Texas (East)	7
Texas (Gulf Coast)	56
Texas (North)	30
Texas (West)	128
Wyoming	74
Other or unknown	9
Total	457

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[1]References given at end of paper.

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the curve at GOR's of 0, 50, 100, 200, 300, 400, 600, 800, 1,000, 1,200, 1,400 and 1,600 scf/bbl. Most of the samples were in the lower range of GOR's.

Viscosity data for each GOR were then plotted on logarithmic coordinate paper with the viscosity of the oil at 0 GOR as the abscissa and the viscosity at any of the other GOR's as the ordinate. For each GOR the data appeared to lie about a straight line. The best fitting lines were determined by the method of least squares with a digital computer. It should be noted that the least squares fit was applied to the logarithms of the viscosities, and some bias was introduced by the logarithmic transformation.

The computed intercepts, *a*, and slopes, *b*, of the best-fit lines are presented in Table 2. Also shown in the table are the anti-logarithms, *A*, of the intercepts and confidence limits for the intercepts and slopes. The values of *A* and *b* are plotted against solution GOR in Fig. 1. It may be seen from Table 2 and Fig. 1 that the change in the computed slope with GOR is not smooth and consistent. This behavior may be explained by the fact that the data for each GOR were processed independently. The scarcity of data for the high GOR's combined with the greater scattering of viscosity data points in this range, cause the computed slope to be erratic at GOR's above 1,000.

Since there is no theoretical reason why the slope should not change in a consistent manner, the best visual curve was drawn through the computed points as shown in Fig. 1. This smooth curve of the slope is, in effect, a simultaneous correlation of the data for all of the GOR's as a whole. The most weight has been given to the points at the low GOR's since they are based on more data. Values of the slope read from this smooth curve at the various GOR's are presented in Table 3.

As shown in Fig. 1 the intercepts lie very closely to a smooth curve and do not show the erratic behavior at high GOR's that the slopes did. Since these points are the y-intercepts at dead oil viscosities of 1 cp, they lie near the center of the line or of the data range at the high GOR's. Therefore, they are only slightly affected by the factors responsible for error in the slopes. Values of the intercept read from the smooth curve at the selected GOR's are presented in Table 3.

These smoothed values of the slope and intercept were used to compute the correlation lines of Fig. 2. Also shown in Table 3 are the ranges of the viscosity data which govern the extent of these lines.

THE CORRELATION

Figs. 1 and 2 each represent a different form of the correlation. Both forms give the same relation among the following three variables: (1) viscosity of the dead oil at reservoir temperature and atmospheric pressure, (2) viscosity of the gas-saturated oil at the same temperature and saturation pressure, and (3) solution GOR of the gas-saturated oil.

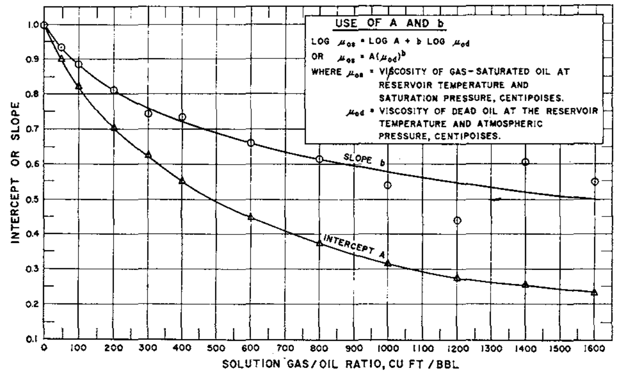

FIG. 1—INTERCEPTS AND SLOPES FOR VISCOSITY CORRELATION LINES.

If any two of these variables are known, the third can be estimated from the correlation. Basically, this correlation predicts the change in viscosity when a known amount of gas is added or removed from an oil of known viscosity. Therefore, it should be applicable to the oil and gas from any of the usual liberation processes, even though differential liberation data were used in its development.

Fig. 1 gives the relation between solution GOR and the values of the intercept *A* and slope *b* for the equation,

$$\log \mu_{os} = \log A + b \log \mu_{od} \quad , \quad . \quad . \quad . \quad . \quad (1)$$

where μ_{os} is viscosity of gas-saturated oil at reservoir temperature and saturation pressure, cp; μ_{od} is viscosity of the dead oil at the same temperature and atmospheric pressure, cp; and log = common logarithm.

In using Fig. 1 to find the viscosity of a crude oil saturated with a certain amount of gas, the values of *A* and *b* for this GOR are read from the curves. These values and the dead oil viscosity are then substituted into Eq. 1 or into its alternate form,

$$\mu_{os} = A(\mu_{od})^b \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

This procedure permits the prediction of the gas-saturated oil viscosity for any GOR and dead oil viscosity within the correlation range without the need for interpolation between curves.

Fig. 2 presents the basic correlation in graphical form—the gas-saturated oil viscosity is plotted against the dead oil viscosity and a straight line is obtained for each GOR. The slopes and intercepts of these lines were obtained from the curves of Fig. 1; these values are also tabulated in Table 3. The solid portions of the lines represent the range of the data used in the correlation while the dashed portions are extrapolations.

The procedure for using Fig. 2 to find the viscosity of a gas-saturated oil is as follows: (1) the viscosity of the dead oil at the reservoir temperature and atmospheric pressure and also the solution GOR of the gas-

TABLE 2—COMPUTED INTERCEPTS AND SLOPES OF CORRELATION LINES

Sol. GOR	No. of data points	Intercept *a*	Slope *b*	Antilog of *a* (*A*)	95 per cent confidence limits: intercept *a*	95 per cent confidence limits: slope *b*
50	457	−0.04659	0.9314	0.8983	±0.00362	±0.00734
100	437	−0.08631	0.8841	0.8198	±0.00487	±0.01007
200	376	−0.15301	0.8110	0.7030	±0.00600	±0.01375
300	323	−0.20477	0.7433	0.6241	±0.00728	±0.01833
400	245	−0.25930	0.7342	0.5504	±0.00799	±0.02462
600	144	−0.35017	0.6599	0.4465	±0.00946	±0.03815
800	101	−0.42863	0.6152	0.3727	±0.01411	±0.06312
1,000	71	−0.50548	0.5406	0.3123	±0.01683	±0.08311
1,200	49	−0.56331	0.4396	0.2733	±0.02241	±0.15229
1,400	32	−0.59413	0.6056	0.2546	±0.02340	±0.15763
1,600	22	−0.63584	0.5473	0.2313	±0.04296	±0.26339
Total	2,257					

TABLE 3—SMOOTHED VALUES OF INTERCEPTS AND SLOPES AND RANGE OF VISCOSITY DATA

GOR (cu ft/bbl)	Intercept *A*	Slope *b*	Viscosity range of dead oil (cp)
0	1.000	1.000	—
50	0.898	0.931	0.377 — 50.0
100	0.820	0.884	0.377 — 50.0
200	0.703	0.811	0.377 — 50.0
300	0.621	0.761	0.377 — 14.2
400	0.550	0.721	0.377 — 8.7
600	0.447	0.660	0.377 — 5.10
800	0.373	0.615	0.377 — 3.95
1,000	0.312	0.578	0.377 — 3.74
1,200	0.273	0.548	0.478 — 1.84
1,400	0.251	0.522	0.478 — 1.59
1,600	0.234	0.498	0.478 — 1.20

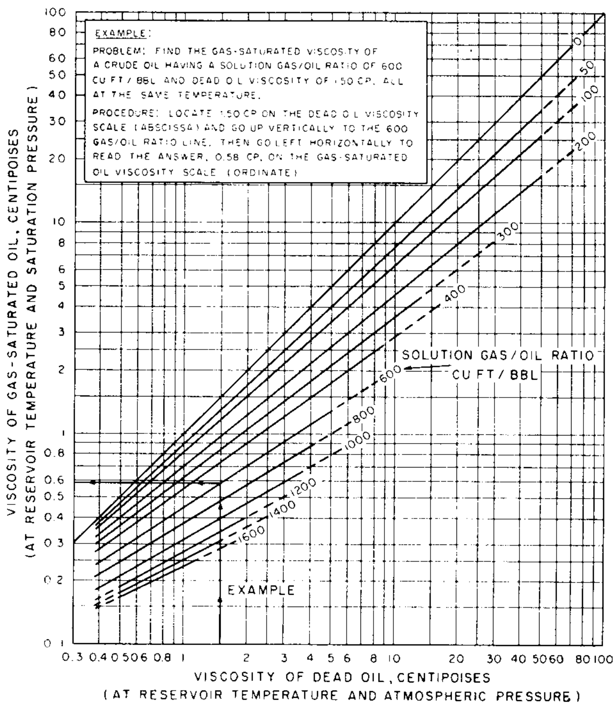

FIG. 2—VISCOSITY OF GAS-SATURATED CRUDE OILS AT RESERVOIR TEMPERATURE AND PRESSURE.

saturated oil must be known; (2) locate the value of dead oil viscosity on the abscissa and go up vertically until the desired solution GOR is reached; and, (3) move left horizontally to the ordinate and read the viscosity of this oil, saturated with the given amount of gas at the same temperature and at its saturation pressure.

This procedure may be reversed to find the dead oil viscosity if the viscosity of the gas-saturated oil is known. Also, if the viscosity of an oil with one solution GOR is known, its viscosity with another solution GOR can be found.

It should be noted that the information from either Fig. 1 or Fig. 2 can be made into a plot of gas-saturated oil viscosity against solution GOR to give a family of curves with the dead oil viscosity as the parameter. The form of such a plot on semi-logarithmic coordinate paper would correspond to that of Beal's correlation[1].

In using the correlation to obtain the viscosity of a gas-saturated oil, it is, of course, important to use as nearly accurate values of dead oil viscosity and solution GOR as possible. Measured values are preferable, but if these are not available, estimated values can be obtained from correlations with other variables. Correlations of dead oil viscosity with oil gravity and temperature and of solution GOR with saturation pressure and oil gravity have been reported by Beal[1]. Correlations of solution GOR with saturation pressure, gas gravity, tank oil gravity and temperature have been presented by Standing[2] and by Lasater[3].

The fit of laboratory-measured viscosity values to the correlation is illustrated in terms of 95 per cent confidence limits. These confidence limits mean that for particular values of dead oil viscosities there is 95 per cent confidence in the statement that the arithmetic mean of the gas-saturated oil viscosities will lie within the interval defined by the limits. Table 4 presents examples of confidence limits of correlation lines for GOR's of 50 and 800. It is seen that the confidence limits are narrowest at the weighted mean value of the dead

TABLE 4—CONFIDENCE LIMITS OF CORRELATION LINES

Sol. GOR (cu ft/bbl)	Visc. of dead oil (cp)	Viscosity of Gas-Saturated Oil: Value from correlation (cp)	95 per cent Confidence Limits: Upper (cp)	Upper (per cent)	Lower (cp)	Lower (per cent)
50	0.38	0.365	+0.005	+1.37	−0.005	−1.37
50	0.60	0.558	+0.006	+1.08	−0.006	−1.08
50	1.00	0.898	+0.008	+0.89	−0.008	−0.89
50	2.38 (mean)	2.02	+0.011	+0.54	−0.011	−0.54
50	3.00	2.50	+0.014	+0.56	−0.014	−0.56
50	6.00	4.77	+0.04	+0.84	−0.04	−0.84
50	10.0	7.67	+0.09	+1.17	−0.09	−1.17
50	20.0	14.6	+0.24	+1.64	−0.24	−1.64
50	50.0	34.3	+0.80	+2.33	−0.79	−2.30
800	0.38	0.206	+0.016	+7.77	−0.015	−7.28
800	0.60	0.272	+0.015	+5.51	−0.014	−5.15
800	0.90	0.349	+0.013	+3.72	−0.012	−3.44
800	1.18 (mean)	0.412	+0.013	+3.15	−0.012	−2.91
800	2.00	0.571	+0.026	+4.55	−0.025	−4.37
800	3.00	0.733	+0.050	+6.82	−0.047	−6.41
800	4.00	0.874	+0.075	+8.58	−0.069	−7.89

oil viscosity range and increase towards each end of the range. The upper and lower limits are not symmetrical because of the logarithmic transformation. The confidence limits increase with GOR, and these given here serve to illustrate their trend and magnitude.

It is emphasized that the confidence limits apply to the fit of laboratory-measured viscosity values to the correlation and not necessarily the fit of the true viscosity values. Laboratory measurements of the viscosity of oils with gas in solution are subject to many sources of error. Some of these sources of error are in the measurements of pressure, temperature, density, gas in solution, angle position and roll time. Other sources are non-equilibrium conditions, calibration errors and variations in techniques, equipment and personnel. Comparative measurements by five different laboratories on one sample showed a spread in the viscosity data which was of the order of 20 per cent of the average viscosity value for the same measured amount of gas in solution. There is no reason to expect that routine measurements of viscosity by various laboratories would normally agree any more closely than the results of this case. Therefore, it is believed that the correlation can predict the viscosities of gas-saturated crude oils with a reliability approaching that of a routine laboratory measurement.

CONCLUSIONS

1. The correlation is generally applicable to a large number of producing areas.
2. In most cases, with this correlation, the viscosities of gas-saturated crude oils can be estimated with a reliability approaching that of a routine laboratory measurement.

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