Table 3

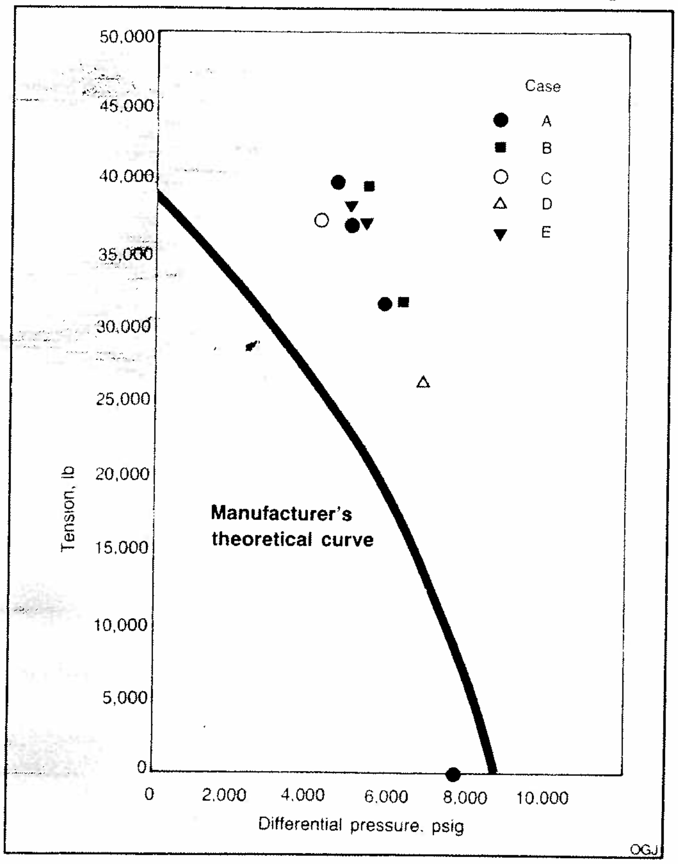
Test 2 results

Case	A	B	C	D	E
	ΔP(psig)Test 2 New coil 0.109 in. W.T.	ΔP(psig)Test 2 New coil 0.109 in. W.T.	ΔP(psig)Test 2 New coil w/weld 0.109 in. W.T.	ΔP(psig)Test 2 New coil w/weld 0.109 in. W.T.	ΔP(psig)Test 2 New coil 0.109 in. W.T. Multi Press/Ten
	65° F.	-31° F.	65° F.	-26° F.	-22° F.
Tension, lb					
0	7,800		0	0	
26,500				6,800	
31,800	5,900	6,300			
37,100	5,000		4,200		5,200
37,100	5,000				
38,425					5,000
39,725	4,600	5,400			

Test 2 was conducted at Calgary with specially built test chamber
Temperature was controlled by circulating methanol through liquid nitrogen

Fig. 5

Collapse tests for 1.75-in. coiled tubing



Failure generally occurred during Test 1 between the lower pipe ram and the pack-off (where the coil was visually necked down), while in Test 2 collapse usually occurred at the midpoint of applied tension.

Damaged tubing

Significant differences in collapse resistance was observed between undamaged and visibly damaged 1.5-in. tubing.

It is important that tubing be free of damage such as egging or gouging.

Tubing life

With the exception of a single test, all 1.5-in. tubing tested has between 200,000 and 400,000 running ft and came from the beginning of the spool (first in the hole) or between 8,000 and 10,000 ft into the spool.

Tubing from different areas of the spool may show varying results.

It should be noted that experience in the western operating area at Prudhoe Bay shows 400,000 running ft (≈40 jobs) to be the useful life of a spool of tubing; any further use dramatically increases the chance of tubing failure.

Tubing size

All 1.75-in. tubing tested was new, and collapse resistance of used 1.75-in. tubing may be affected differently than the used 1.5-in. tubing.

Further, the new 1.75-in. tubing samples tested were slighly egged, from 1.69 to 1.82-in. OD.

Collapse resistance

The surge/cycle tests of 1.75-in. tubing at cold temperature showed a 10% loss in collapse resistance vs. the straight cold temperature tests.

Repeated pressure shocks to 1.5-in. tubing also caused some loss in collapse resistance. Further testing in this area is needed.

Butt welds

Two tests were done on butt-welded, 1.75-in. tubing, one at 65° F. and one at −26° F.

The higher temperature test showed a 16% loss in collapse strength while the cold temperature test was in line with other tests.

Tension

Given the limited number of tests across the entire range of tension vs. differential pressure possibilities, caution must be used in areas where few tests were performed. ▪

Correlation

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A new correlation estimates the viscosity of Saudi crude oils in the undersaturated oil regions as a function of pressure, temperature, and API-gravity.

Field data of 182 crude oil samples obtained from the major producing areas of Saudi reservoirs were statistically treated and used to derive the viscosity correlation.

The accuracy of the developed correlation was determined using statistical error analysis. Statistical error analysis techniques were employed to check the validity of the developed correlation as compared to other published crude oil viscosity correlations using the field data of Saudi reservoirs.

The results show that the developed correlation provides a more accurate estimation of crude oil viscosity with an average relative error of −13.58%.

The development of viscosity correlations has received considerable attention in petroleum research. Of particular interest, it is required in the calculations of simulation studies of two and multi-phase flow in vertical and horizontal pipes, well testing, and design of production equipment.

In view of the different correlations proposed for estimating the viscosity of crude oils above the bubble point, there are two main distinct approaches: compositional dependence and compositional independence.

Lohrenz, et al.,[1] Lowal,[2] Saeedi and Rowe,[3] and Little and Kennedy,[4] conducted the investigation of the first ap-

estimates Saudi crude oil viscosity

proach. Their developed correlations were based on the compositions of the studied crude oils at desired pressure and temperature.

The compositional independence correlations were expressed as functions of pressure, temperature, and bubble point pressure and viscosity.

Beal,[5] Vazquez,[6] and Khan, et al.,[7] developed different empirical correlations for predicting crude oil viscosity above bubble point. The advantages and defects of each approach are outlined in Table 1.

This table clearly indicates that, although the compositional dependence approach is more accurate than compositional independence, it makes viscosity prediction more complex and less useful for practical purposes. Therefore, the collected field data of Saudi crude oils were used to develop the new empirical correlation for viscosity as a function of pressure, temperature, and API gravity.

The developed correlation should be applied to crude oils that exist above the bubble point pressure. The parameters used in the correlation were statistically treated to determine the confidence levels at which the evidence of the developed correlation should be judged.

The accuracy of the developed correlation was determined using statistical error analysis.[8] This involved the calculation of the Durbin-Watson statistic, correlation coefficient, average relative error, and graphical representation of the errors (crossplot).

Correlation development

The present study starts with the investigation of the reservoir parameters that affect the estimation of oil viscosity above the bubble point. Preference was given to those parameters which could be easily and commonly measured in the field or in the laboratory.

It was found that, above the bubble point, the only reservoir parameters that can affect oil viscosity are pressure, temperature, and API gravity. Neither solution gas-to-oil ratio (GOR) nor oil composition improved the accuracy of the correlation to any significant extent.

This is due to the fact that both solution GOR and oil composition are almost constant above the bubble point. Therefore, the field data of viscosity, pressure, temperature, and API gravity on a total of 182 crude oil samples obtained from the major producing areas of the Saudi reservoirs, were used to derive the desired correlation.

Before proceeding to discuss the technique used to derive the viscosity correla-

Table 1

Compositional dependence and independence approaches

Approach	Advantages	Defects
Compositional dependence	It is commonly used in simulation studies.	It depends on the accuracy of the method used to predict density.
	It is more accurate than the compositional independence approach.	It cannot be used at the critical temperature and pressure of multicomponent mixtures.
		It is less useful for practical purposes.
Compositional Independence	It is commonly used in multiphase flow, well testing, and design of production equipment	It is less accurate than the compositional dependence approach.
	It could easily be tuned to match experimental data.	It cannot clearly explain the behavior of oil viscosity.
	It has simpler mathematical expressions than the compositional dependence approach.	

Nomenclature

- P = Reservoir pressure, psi
- PR (z) = Probability
- T = Reservoir temperature, °F.
- z_1, z_2 = Higher and lower values of standard variate
- μ = Viscosity, cp
- API = $141.5/\gamma_o - 131.5$, °API
- γ_o = Specific gravity of crude oil

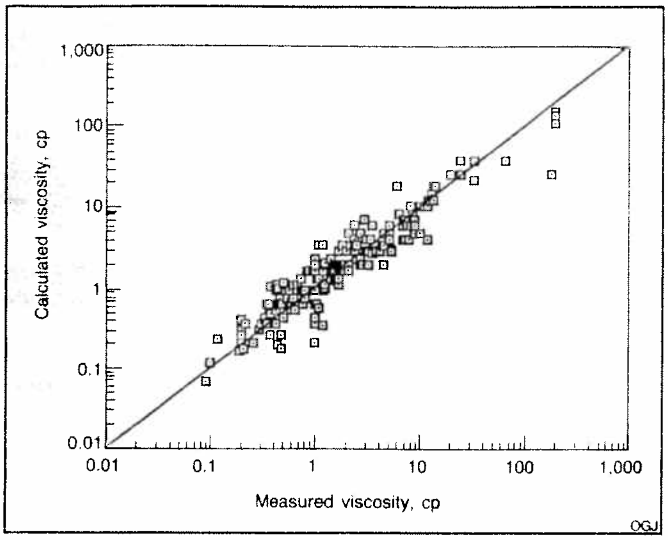
Table 2

Probabilities and confidence levels of normally distributed reservoir parameters

Reservoir parameter	No. of data points	Mean	Standard deviation	Maximum value (z_1)	Minimum value (z_2)	Probability ($z_1 \leq z \leq z_2$)	Confidence level
Pressure, psi	182	3,780	1,296	5.61	2.620	0.988	0.976
Temperature, °F.	182	197.3	32.4	3.170	3.280	0.998	0.996
Gravity, °API	182	31.19	6.82	2.640	3.470	0.995	0.990
Viscosity, cp	182	6.9	25	7.724	0.272	0.898	0.796

Fig. 1

Calculated viscosities vs. measured data



tion, it might be advisable to check first the normality of the distribution of the reservoir parameters. This is the basis for statistical judgments.

In terms of a standard normal variate, the probability of a normally distributed variable is expressed by the following probability density equation.[8]

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Desouky

$$PR\ (z_2 < z < z_1) = 1/\sqrt{2\pi} \int_{z_1}^{z_2} e^{-z^2/2}\, dz \quad (1)$$

Equation 1 was used to check the normality of the reservoir parameters distribution. The results are given in Table 2.

This table shows that the estimated variabilities and confidence levels for normally distributed parameters are ranged from 0.898 to 0.998, and from 0.796 to 0.996, respectively. Applying the multiple linear regression technique to the data of the Saudi reservoirs, the following correlation for crude oil viscosity above bubble point was derived:

$$\mu = 8.06 \times 10^5 \; e^{(-0.174\,API + 77 \times 10^{-5}\,P)/T^{1.49}} \quad (2)$$

Correlation accuracy

In order to determine the accuracy of the developed correlation, statistical error analyses have been carried out. This involved the calculations of the Durbin-Watson statistic (DWS), correlation coefficient, average relative error, and graphical representation of errors (crossplot).

The results show that the values of DWS, correlation coefficient, and the average deviation between the field data and those estimated from Equation 2 were 1.66, 0.926, and −13.58%, respectively.

The values of these statistical measures emphasize the evidence of the accuracy of the developed viscosity correlation relative to the field data at the tested confidence level.

In addition, the field data are plotted against the estimated ones, and a 45° straight line is drawn on the same plot as shown in Fig. 1. This figure reveals the closeness of the plotted data points to the 45° straight line. This ensures a good fit of the data to the curve.

Comparisons

Equation 2 and Beal and Vazquez correlations were used to estimate the viscosity of Saudi crude oils above the bubble point.

Table 3

Correlation comparisons

Correlation	Average percent relative error
Present work, 1989	−13.584
Beal, 1946	32.073
Vazquez, 1976	−82.587

Following this, a comparison was made between the measured viscosity of Saudi crude oils and the calculated ones.

The results are given in Table 3, from which it can be observed that the developed correlation reveals the least average absolute relative error.

Hence, the developed correlation should be valid for either Saudi crude oils or other crude oils falling within the range of data used in the study.

Acknowledgment

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