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**IMPROVED K-FACTORS CORRELATION FOR YEMENI CRUDE OIL
COMPONENTS USING PVT LABORATORY DATA**

**УЛУЧШЕННАЯ КОРРЕЛЯЦИЯ К-ФАКТОРОВ ДЛЯ КОМПОНЕНТОВ
ЙЕМЕНСКОЙ СЫРОЙ НЕФТИ С ИСПОЛЬЗОВАНИЕМ
ЛАБОРАТОРНЫХ ДАННЫХ ДОТ**

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Abstract. In this study, the laboratory data for different Yemeni crude oil sample are used to test accuracy of empirical correlations used for predicting crude oil equilibrium ratio. Statistical techniques were used to evaluate these correlations. Statistical comparison of currently published correlations shows that absolute relative error range between 548% and 748.97% An improved correlation for Yemeni crude oil is developed for predicting K-values. This correlation was obtained by multiple-linear regression analysis. The new K-factors correlation was found to be an improvement over most published correlation.

Аннотация. В данной статье приводятся лабораторные данные для различных образцов Йеменской сырой нефти, которые используются для тестирования точности эмпирических связей, необходимых для прогнозирования коэффициента равновесия сырой нефти. Статистические методы были использованы для оценки этих связей. Статистическое сравнение представленных на данный момент связей показывает, что абсолютная относительная погрешность варьируется в пределах от 548% до 748.97%. Улучшенная корреляция для Йеменской сырой нефти разработана для прогнозирования K-величин. Эта корреляция была получена с помощью многолинейного анализа регрессии. Были найдены новые корреляции K-факторов для улучшения самых последних корреляций.

Keywords: Yemeni crude oil, statistical analysis, K-factors.

Ключевые слова: Йеменская сырая нефть, статистический анализ, K-факторы.

Introduction

Equilibrium ratio plays an important role in petroleum and chemical engineering calculations. It is important in solving phase equilibrium problems in reservoir and process engineering. K-factors have many applications in surface separator calculations, in determination of dew point pressure, bubble point pressure. They used to find the number of stage of separation and determine the optimum pressure of separation.

In a multicomponent system, the equilibrium ratio K_i of a given component is defined as the ratio of the mole fraction of the component in the gas phase y_i to the mole fraction of the component in the liquid phase x_i , known as K-values or K-factors.

Mathematically, the relationship is expressed as:

$$K_i = \frac{y_i}{x_i} \quad (1)$$

In this work we focus on the most common used empirical correlations namely the Wilson and Standing correlations [1,3] and their viability is tested for Yemeni data. Using multi-variable regression analysis an improved correlation for estimating K-factors for Yemeni crude oil is provided.

Prediction methods of K-values

Several empirical methods have been proposed for establishing equilibrium constant for the components of crude oil [3-6]. These methods were reviewed by Tarek Ahmad [2]. The correlations used in this work are summarized in Table (appendix A).

Data source

About 900 K-values extracted from laboratory PVT analysis. The database was constructed from differential liberation data and multi-stage separation tests. A description of the data utilized in the development of correlation is shown in table 1. The range of mole fraction for the components of crude oil is shown in table.

Table 1. Data used in this work

PVT Property	Range
Pressure, psia	30-3060
Temperature, F	80-220
Formation volume factor, bbl/STB	1-1.678
Gas-oil ratio, scf/STB	2-1032.4
Oil density, lb/cu ft	40.37-56.54
Bubble point pressure, psia	39-3365

Table 2. Range of mole fraction for reservoir fluid used

Component	Mole fraction
N ₂	0.0007-0.0113
CO ₂	0.0001-0.0057
H ₂ S	0.0001-0.0109
C ₁	0.001-0.43067
C ₂	0.0003-0.0872
C ₃	0.001-0.0934
i-C ₄	0.0005-0.0178
n-C ₄	0.0012-0.0572
i-C ₅	0.0012-0.0195
n-C ₅	0.0019-0.0304
C ₆	0.0172-0.0384
C ₇₊	0.3121-0.9701

Extracting K-values from laboratory data

The data set used in the study consists of 900 data points that represent different Yemeni crude oils. These data were obtained from laboratory tests namely differential liberation (DL) and separation tests. The following experimental PVT data are required for calculations of K- values :

- Compositional analysis of reservoir/ well fluid, z_j
- Average molecular weight , MW
- Oil density and the oil formation volume factor at the bubble point, ρ_{or}, B_{ob}
- Gas-oil ratio for each separation stage, R_{sp}
- Compositional analysis for gas existing at each stage, y_j

The procedure is summarized in the following steps [11]:

- Evaluate the gas mole fraction as :

$$n_{gi} = \frac{R_{si} M_{or} \cdot n_{L(i+1)} \dots n_{L(\text{final}-1)}}{2138 \cdot B_o \cdot \rho_{or}} \quad (2)$$

- Calculation the liquid mole fraction for each stage using material balance given the feed mole fraction and the gas mole fraction, y_i :

$$X_i = \frac{z_i - n_g \cdot y_i}{(1 - n_g)} \quad (3)$$

- Calculation K-factors by equation (1).

Example of calculation is given in table 3.

Table 3. K-factors from DL for well-Sunah field

Component	Z	MW	Y	Z·MW	X	K
N ₂	0.0113	28.013	0.028	0.316547	0.0016	17.27422
CO ₂	0.0026	44.01	0.0056	0.114426	0.0009	6.50224
C ₁	0.2683	16.043	0.6954	4.304337	0.0208	33.49908
C ₂	0.0872	30.07	0.1356	2.622104	0.0591	2.292553
C ₃	0.0869	44.097	0.0811	3.832029	0.0903	0.898499
i-C ₄	0.0136	58.123	0.0083	0.790473	0.0167	0.497846
n-C ₄	0.0456	58.123	0.0226	2.650409	0.0589	0.383503
i-C ₅	0.0147	72.15	0.0049	1.060605	0.0204	0.240432
n-C ₅	0.0264	72.15	0.0065	1.90476	0.0379	0.171351
C ₆	0.0302	86.18	0.0048	2.602636	0.0449	0.106853
C ₇₊	0.4132	229.5	0.0073	94.8294	0.6485	0.011258

Data:

P=915, psia , T= 220 °F, R _{sp} = 689 , Bo= 1.673bbl/STB , MW= 115 , n _g =0.503

Discussion

Experimentally extracted K-values from laboratory data [7] in this study are compared against empirically predicted values from the Wilson correlation, Standing correlation and the proposed correlation. The developed correlation for Yemeni oil based on standing correlation. This correlation was obtained by multiple linear regression analysis. The general form of proposed correlation of K-values:

$$K = \frac{10^{(a_1+a_2+a_3)+F(a_4+a_5+a_6)}}{p} \quad (4)$$

The multi-variable regression technique was used to obtain the best values for a_1 , a_2 , a_3 , a_4 , a_5 , a_6 , and b , T_b . The new correlating parameters are given in table 4.

Separate parameters were obtained for individual components, C₇₊ and non-hydrocarbon components. For C₇₊ pseudo-component, the Riazi-Daubert [10] correlation was used for calculating of T_b , T_c , P_c and b .

Table 4. Constants for the new proposed correlation for Yemeni crudes

Component	a_1	a_2	a_3	a_4	a_5	a_6	b	T_b
N ₂	0.034	0.0005	1.50E-07	0.89	-0.0002	-3.50E-08	326.558	110.255
CO ₂	1.200	-0.0006	1.50E-07	0.16	-0.0002	-3.50E-08	558.358	193.7714
C ₁	1.200	0.0007	1.50E-07	0.89	-0.0002	-3.50E-08	202.251	126.179
C ₂	1.177	0.0005	1.3E-07	0.89	-0.0002	-3.50E-08	1024.090	288.933
C ₃	0.793	0.0005	1.5E-07	0.89	-0.0002	-3.5E-08	1803.666	416.056
i-C ₄	0.832	0.0005	1.5E-07	0.89	-0.0002	-3.5E-08	913.065	286.285
n-C ₄	0.652	0.0005	1.3E-07	0.88999	-7E-05	-5.9E-08	2155.081	491.122
i-C ₅	0.944	0.0004	1.3E-07	0.8898	-2E-05	-6.69E-08	2581.375	556.727
n-C ₅	0.928	0.0003	1.3E-07	0.89295	-4E-05	-6.05E-08	1299.764	571.320
C ₆	1.092	0.0002	1.2E-07	0.89829	-5E-05	-3.5E-08	524.824	623.931
C ₇₊	0.188	0.0001	1.5E-07	0.89	-0.0002	-3.5E-08		

For the published correlation and proposed correlation statistical comparison is conducted with extracted values of equilibrium constants.

A comparison between actual and predicted values of equilibrium ratio using correlations for all components is shown in figures 1-3.

High values in the figure represent K-factors for N₂, CO₂ while small value represents K-values for C₇₊.

As it shown the Wilson correlation underestimate significantly the experimental K-values for n-C₄, n-C₅ Component. While the Standing correlation over estimated extracted K-values for N₂ Component. The calculated values using the proposed correlation match the experimental values closely.

Table 5 lists statistical parameters for the three correlations. It shows that the proposed correlation give a significant improvement in estimation of K-values over the Standing and Wilson correlations.

The statistical parameters for the C₁-C₆ components are summarized in tables 6 and 7. The APRE for component low error is observed for C₂ while for other components error is high

The new correlation shows reduced values of APRE for all components C₁-C₆ 2929.51% for Wilson and 368.18 % for standing to 76.91%

Clearly demonstrated that proposed correlation give better prediction of K-values than all empirical correlations.

Table 8 lists the statistical analysis of three correlations against of the experimental K-Values for C₇₊ component. The statistical parameters presented in the table indicate that the correlation of this study provides lower average relative and absolute error and slightly standard deviation. The improvement over Wilson is from

100.7 to 83.9% This improvement is due to tuning the coefficients $a_1, a_2, a_3, a_4, a_5, a_6$, in the correlation.

Table 9 represents statistical parameters for non-hydrocarbon components. It shows that the proposed correlation significantly improves the accuracy of predictions of values. This shown by reducing average error from above 1000 for both correlations to 90.67 % for CO₂ and from above 4000% to 76.81 % for N₂. This improvement is due to adjustment of coefficients a_1-a_6 and T_b, b .

For CO₂ and N₂ K-values were poorly predicted by Wilson and Standing correlations. The predicted K-values by Wilson overestimated the extracted values.

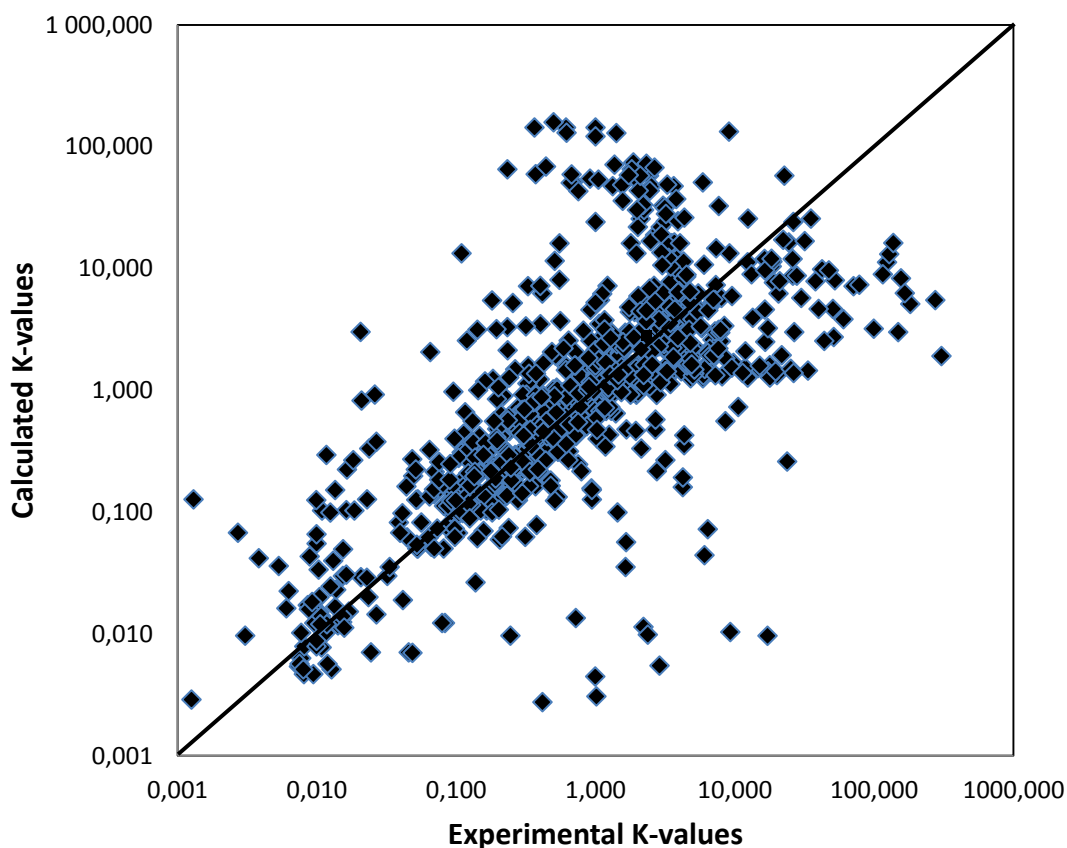


Figure1. Crossplot for K-values (Standing correlation)

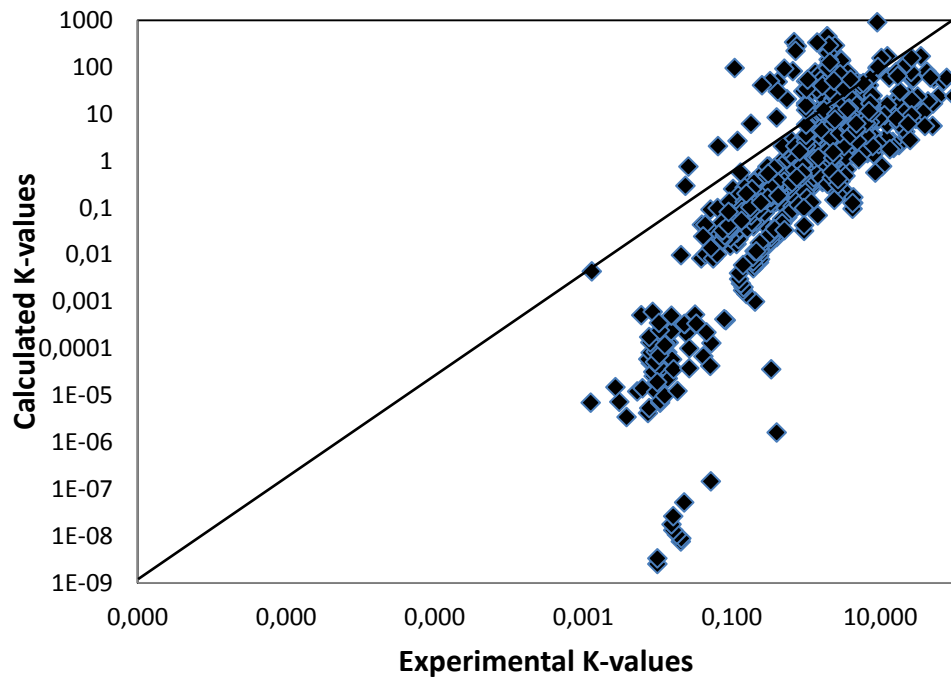


Figure 2. Crossplot for K-values (Wilson correlation)

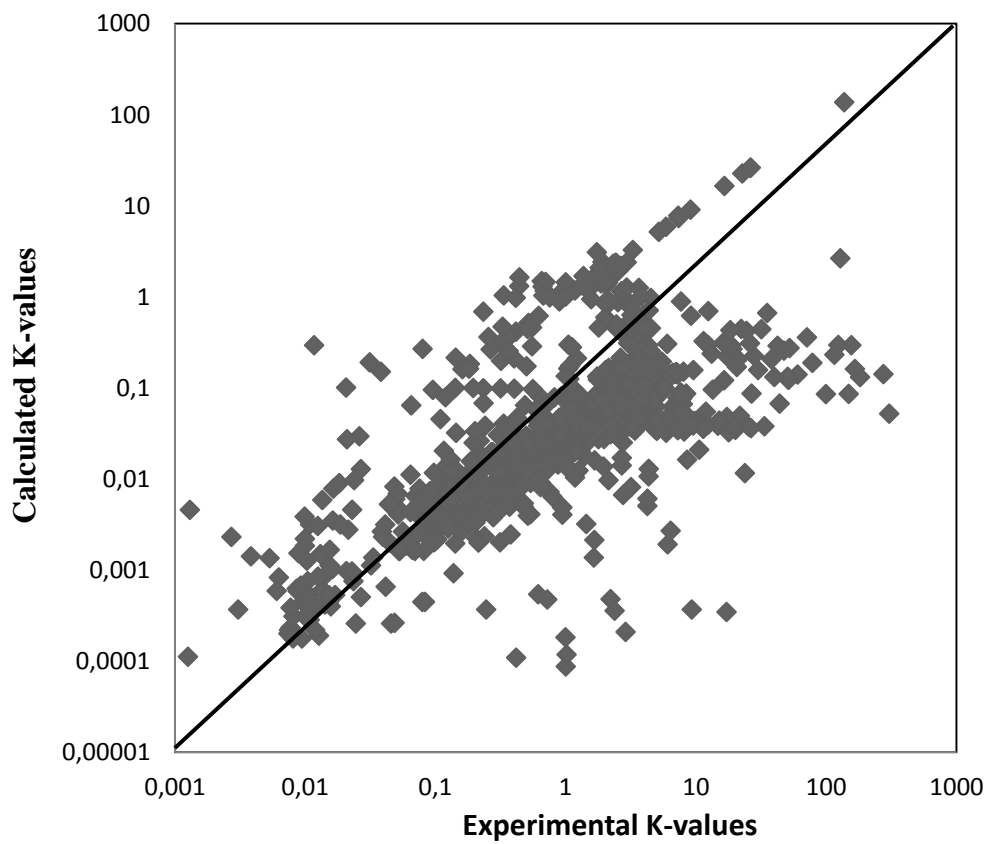


Figure 3. Crossplot for K-factors (new proposed correlation)

Table 5 Statistical parameters of three correlations for all components

Component	Standing				Wilson				New correlation			
	APRE	E _{RMS}	SD	C.V	APRE	E _{RMS}	SD	C.V	APRE	E _{RMS}	SD	C.V
All	548.62	2711.33	111.51	0.42	748.97	4451.99	111.50	0.26	93.22	125.75	111.53	8.72

Table 6 Comparison of the three correlations for C₁- C₆ components

Component	Standing				Wilson				New correlation			
	APRE	E _{RMS}	SD	C.V	APRE	E _{RMS}	SD	C.V	APRE	E _{RMS}	SD	C.V
C ₁	99.90	251.18	162.81	14.18	1474.61	3557.02	130.77	0.96	60.11	156.41	164.15	22.77
C ₂	67.84	169.29	1191.01	6.52	744.59	1967.23	35.85	0.50	33.43	77.12	1725.47	14.32
C ₃	151.23	404.19	1805.27	0.79	184.98	536.76	7.11	0.60	50.69	58.57	1731.77	5.57
i-C ₄	151.23	404.19	1805.27	0.79	184.98	3669.03	536.76	7.11	49.48	57.43	1895.00	5.69
n-C ₄	137.55	385.05	2165.18	0.34	129.24	402.52	1.68	0.32	50.23	62.91	1935.38	2.06
i-C ₅	95.93	203.00	2397.37	0.64	129.24	402.52	1.68	0.32	54.71	64.76	2241.97	2.00
n-C ₅	128.35	394.81	2496.57	0.18	100.60	345.66	1.13	0.21	35.22	46.49	2346.02	1.53
C ₆	156.53	474.10	2720.07	0.08	102.36	320.67	0.62	0.11	38.49	65.33	2826.72	0.56

Table 7 Comparison of three correlations for All C1-C6 components

Component	Standing				Wilson				New correlation			
	APRE	E _{RMS}	SD	C.V	APRE	E _{RMS}	SD	C.V	APRE	E _{RMS}	SD	C.V
C ₁ -C ₆	368.18	1544.36	40.72	0.34	2929.51	32819.63	41.49	0.02	76.91	88.09	40.72	5.90

Table 8 Statistical comparison of three correlations for C₇₊ component

Component	Standing				Wilson				New correlation			
	APRE	E _{RMS}	SD	C.V	APRE	E _{RMS}	SD	C.V	APRE	E _{RMS}	SD	C.V
C ₇₊	384.78	1658.42	1.45	0.00	100.74	101.89	1358.35	1325.14	83.922	87.449	1.389	0.051

Table 9 Statistical comparison of three correlation for non-hydrocarbons

Component	Standing				Wilson				New correlation			
	APRE	E _{RMS}	SD	C.V	APRE	E _{RMS}	SD	C.V	APRE	E _{RMS}	SD	C.V
CO ₂	1032.14	13654.08	2815.63	40.06	2594.87	8291.61	465.93	6.61	90.67	96.49	40.01	19.28
N ₂	6173.46	32236.29	336.56	0.21	7320.60	25608.06	380.22	0.89	76.81	94.80	336.39	71.84

Conclusions

- Calculated K-values and experimentally extracted were compared.
- New K-values correlation for Yemeni crude oils has been developed.
- Based on statistical comparison it is clearly shown that the new proposed correlation was found to be an improvement over the published correlations.
- K-factors obtained from two investigated correlations perform relatively well for C₇₊ while perform relatively poor for all components and poorly for non-hydrocarbons.

Appendix A	
Standing's correlation	
	$\log(K_i P) = a + c \cdot F_i$ (A-1)
or	
	$K_i = \frac{1}{p} \times (10)^{(a + c F_i)}$
K _i = the equilibrium constant for the component i.	
	$a = 1.2 + 0.00045 \times P + 15 \times 10^{-8} \times P^2$ (A-2)
	$c = 0.89 - 0.00017 \times P - 3.5 \times 10^{-8} \times P^2$ (A-3)
	$F_i = b_i \left(\frac{1}{T b_i} - \frac{1}{T} \right)$ (A-4)
	$b_i = \frac{\log(P c_i / 14.7)}{\left(\frac{1}{T b_i} \right) - \left(\frac{1}{T_{ci}} \right)}$
For C ₇ ⁺	
	$N = 7.3 + 0.0075(T - 460) + 0.0016 \times P$ (A-5)
	$b = 1013 + 324 N - 4.256 N^2$ (A-6)
	$T_b = 301 + 59.85 N - 0.971 N^2$ (A-7)
Wilson correlation	
	$K_i = \frac{p_{ci}}{p} \exp \left[5.37(1 + \omega_i) \left(1 - \frac{T_{ci}}{T} \right) \right]$ (A-8)

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Nomenclature

- n = total number of moles of the hydrocarbon mixture, lb-mol
 p_{ci} = critical pressure of component i , psia
 p = system pressure, psia
 T_{ci} = critical temperature of component i , °R
 T = system temperature, °R
 a, c = correlation parameters
 B_o = oil formation volume factor, bbl/STB
 F_i = characterization factor for component i
 K_{exp} = extracted K-value
 K_i = equilibrium ratio for component i
 M_{or} = molecular weight of reservoir oil, lbm/lb mol
 M_{STO} = molecular weight of stock-tank oil, lbm/lb mol
 N = number of carbon atoms
 n_{gi} = mole fraction of gas separated in separator stage i , based on 1 lb mol of feed
 n_{Li} = mole fraction of liquid separated in separator stage i , based on 1 lb mol of feed
 R_{ST} = gas to oil ratio in stock-tank, SCF/STB
 R_{Spj} = gas to oil ratio in separator stage j , SCF/STB
 T = Temperature, °R
 T_{bi} = normal boiling point for component i , °R
 T_{ci} = critical temperature for component i , °R
 x_i = mole fraction of component i in liquid phase

y_i = mole fraction of component i in gas (vapor) phase

z_i = mole fraction of component i in feed

ρ_{STO} = density of stock-tank oil, lbm/ft³

ρ_{or} = density of reservoir oil, lbm/ft³

ω_i = acentric factor for component i

R_{sb} = solution gas-oil-ratio at the bubble point, scf/STB

E_{RMS} =the Root Mean Square Error

C.V=the Coefficient of Variation

APRE= Average Absolute Relative Error

SD=standard deviation

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