



Estimation of Extract Yield and Mass Transfer Coefficient in Solvent Extraction of Lubricating Oil

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Abstract

An investigation was conducted to suggest relations for estimating yield and properties of the improved light lubricating oil fraction produced from furfural extraction process by using specified regression.

Mass transfer in mixer-settler has been studied. Mass transfer coefficient of continuous phase, mass transfer coefficient of dispersed phase and the overall mass transfer coefficient extraction of light lube oil distillate fraction by furfural are calculated in addition to all physical properties of individual components and the extraction mixtures.

The effect of extraction variables were studied such as extraction temperature which ranges from 70 to 110°C and solvent to oil ratio which ranges from 1:1 to 4:1 (wt/wt) were studied.

The results of this investigation show that the extract yield E decreased with decreasing solvent to oil ratio in extract layer and increased with increasing temperature. The fraction of total solvent in the raffinate phase decreased with increasing oil to solvent ratio in raffinate layer and increased with increasing temperature. Solvent to oil ratio in extract layer decreased with increasing temperature and increased with increasing solvent to charge oil ratio at constant temperature. Oil to solvent ratio in raffinate decreased with increasing temperature and increased with increasing solvent to charge oil ratio at constant temperature.

Estimated functions are the best modeling function for prediction extraction data at various operating conditions.

Mass transfer coefficient of continuous phase k_c and mass transfer coefficient of dispersed phase k_d are increased with increasing temperature and solvent charge to oil ratio at constant temperature. The overall mass transfer coefficient K_{od} is increased with increasing temperature and solvent to charge oil ratio; while K_{od} is increased with temperature and decreased with solvent to charge oil ratio.

Keywords: Mass transfer coefficient, solvent extraction, modeling, lube oil, furfural

1. Introduction

Base oils made from crude petroleum are made up of a great variety of molecules, which contain aromatic rings, naphthenic rings, paraffin and isoparaffin chains. The hydrocarbons found in mineral oils are mainly of three general types: straight and branched-chain paraffinic compounds, polycyclic and fused-ring saturated hydrocarbons based on cyclopentane and cyclohexan prototype ring structures, collectively known as naphthenes, and aromatics, both mono and polynuclear, which are unsaturated ring structures.

Selective solvent extraction offers a useful method for separating liquid mixtures[1]. Because of the large number of organic compounds

contained in such mixtures, theoretical knowledge of the extraction equilibria which would be of assistance in the solution of practical problems has been meager. There are many theoretical approaches to the solvent extraction of lubricating oil based on the classical laws of physical chemistry. The errors of extrapolation or interpolation in most of these theories can be traced to the use of distribution coefficients and the assumption that the extract and raffinate fractions are pure compounds. Kalichevsky[2] suggested a relation for estimating extract yield for constant number of stages as:

$$\log E = (m+nT) \log S + (p+qT) \quad \dots(1)$$

Since both solvent and oil act as solvents for each other, the modified form of Eqn.1 for calculating the solvent fraction in the raffinate as[3]:

$$\log S_R = (a_1 + bT) \log R + (c + fT) \quad \dots(2)$$

Analysis of constant temperature extraction shows that the extraction yield may be expressed as:

$$\log E = C \log S_E + C^1 \quad \dots(3)$$

And the fraction of the total solvent loss to raffinate is:

$$\log S_R = K \log R + K^1 \quad \dots(4)$$

Assuming a temperature effect similar to that found by Kalichevsky, Equations 3 and 4 become:

$$\log E = (m^1 + n^1 T) \log S_E + (p^1 + q^1 T) \quad \dots(5)$$

$$\log S_R = (a^1 + b^1 T) \log R + (c^1 + f^1 T) \quad \dots(6)$$

Mass Transfer studies in mixer-settler have been mostly confined to estimations of stage efficiency[4, 5]. Few investigations report data on mass transfer coefficients k_c and k_d . The procedure suggested for the estimation of extraction rates in mixer-settlers[6,7] involves the use of the continuous phase coefficient based on solid dissolution studies[6,8,9,10]. As for the application of the solid dissolution model to liquid-liquid systems, Jordan[10] has analyzed the results of Barker and Treybal for liquid-liquid systems by Rushton et al.[11]. The calculated continuous phase of coefficient data of Rushton et al. showed variation with impeller speed; they could be favourably compared for dispersed phase viscosity of 1 cp with the following equation[6]:

$$k_c d_T / D_c = 0.052 (d_R^2 N \rho_c / \mu_c)^{0.833} (\mu_c / \rho_c D_c)^{0.5} \quad \dots(7)$$

The equation was proposed on the bases of data obtained in vessels with $d_T = 0.5-2.5$ ft, $d_R / d_T = 0.25-0.67$ and $x = 0.005-0.232$. However, for high dispersed phase viscosities, viz. 10,50 and 100 cp, the data of Rushton et al.[12] showed wide deviation from the above correlation indicating a pronounced effect due to dispersed phase viscosity as well as impeller speed. The above correlation also fails to correlate data for baffled and unbaffled vessels[13]. On the basis of solid dissolution data, Calderbank[8, 9] suggests the following equation for k_c :

$$k_c (\mu_c / \rho_c D_c)^{2/3} = 0.13 ((P/v) \mu_c / \rho_c^2)^{1/4} \quad \dots(8)$$

The starting point of agitation design is properly a mass transfer coefficient known empirically or from correlations in terms of parameters impeller size and rotation, power input and gas flow rate. Few correlations are in the open literature, but some have come from two of the industries that employ aerated stirred tanks on a large scale[14, 15].

The aim of this research is to obtain a representation of lubricating oil extraction system using specified regression that leads to prediction of extract yield and fraction of total solvent in raffinate phase in addition to determining individual mass transfer coefficient of continuous and dispersed phase and over all mass transfer coefficients based on dispersed phase. This is a theoretical research that depends on data base of Sadiq[16].

2. Results and Discussion

Figure1 shows the effect of solvent to oil ratio in extract phase S_E on the extract yield E in different temperatures. The extract yield decreased with decreasing solvent to oil ratio in extract layer because the extraction efficiency of aromatics and poly aromatics decreased with decreasing solvent to charge oil S . Figure 1 also shows the increasing of extract yield with increasing temperature but in limitation, solvent extraction of oil is usually carried out at temperatures as close as possible to the miscibility temperature of oil-solvent system in order to reduce the necessary solvent to oil ratio and to operate at the lowest possible viscosity of the oil phase in addition to increasing solubility of undesired compounds in furfural which lead to high extract yield. The extraction temperature 212°F is the most close to the miscibility temperature of extraction system in which two phases will be kept immiscible and which allow extraction to be carried out with high extract yield. As temperature increased up to 230°F, the extract yield slightly increased which confirms that further increasing in temperature above 212°F caused the dropping of extraction efficiency because the miscibility temperature of system exceeded.

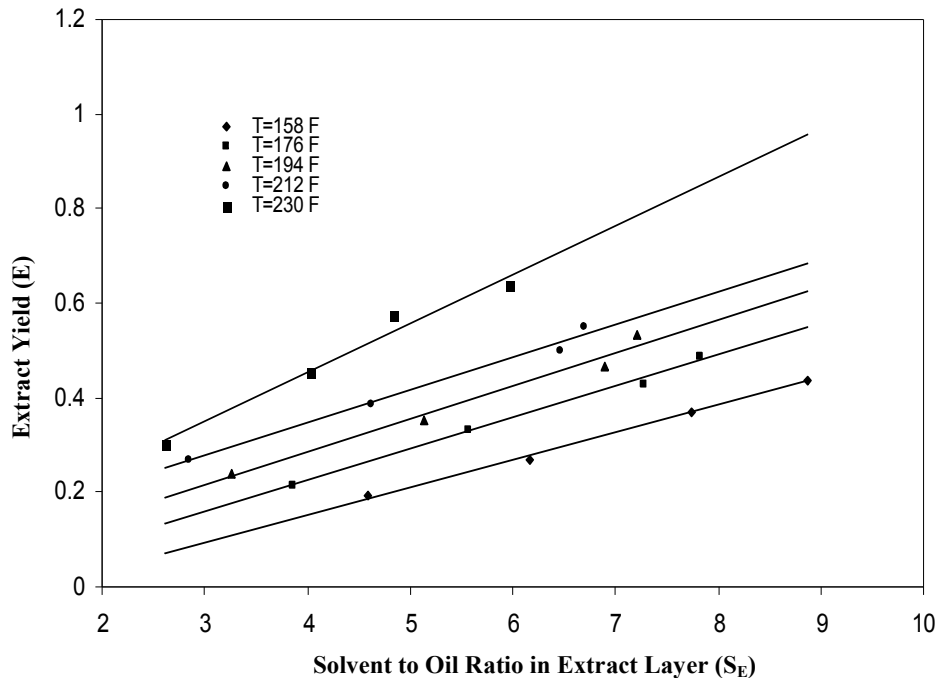


Fig.1. Effect of S_E on E in Extraction of Light Lube Oil by Furfural.

Figure 2 shows the effect of oil to solvent ratio in raffinate layer R on the fraction of total solvent loss to raffinate layer S_R in different temperatures. The fraction of total solvent in the raffinate phase decreased with increasing oil to solvent ratio in raffinate layer because the increasing solvent power (solvent to charge oil ratio) at constant temperature gives high extraction efficiency and as solvent power increased, the solvent in raffinate decreased proportionally with the decreasing of raffinate yield of oil which keeps the increase of R. The reverses of extract phase in which solvent increased, in the solvent power also increased. There is no significant effect of increasing temperature on the fraction of total solvent in the raffinate phase.

Figure 3 shows the effect of temperature on the solvent to oil ratio in extract layer at a given solvent to charge oil ratio. The solvent to oil ratio in extract layer S_E decreased with increasing temperature because the temperature of the extraction has a very great effect on the solubility characteristics of solvent and increasing extraction temperature increases the solubility of undesired compounds in furfural which lead to high extract yield which necessarily decreases solvent in the

extract phase at constant solvent to charge oil ratio. The reverses in raffinate phase in which solvent increased with increasing temperature. While Solvent to oil ratio in extract layer increased with increasing solvent to charge oil ratio at constant temperature because the power of solvent dominates. Figure 4 shows the effect of temperature on the fraction of total solvent in raffinate layer. S_R increased with increasing temperature because as temperature rose close to the miscibility temperature of oil-solvent system which increases the solubility of the undesired compounds in furfural. Decreasing raffinate yield of oil necessarily increases solvent in the raffinate phase at constant solvent to charge oil ratio. Fraction of total solvent in raffinate layer decreased with increasing solvent to charge oil ratio at constant temperature and the reason is that the dropping of temperature effect and the power of solvent dominates. While Oil to solvent ratio in raffinate decreased with increasing temperature because of the reducing solvent for extraction which is increased in raffinate phase rather than extract phase which seems to increase with increasing solvent to charge oil ratio at constant temperature as shown in Figure 5.

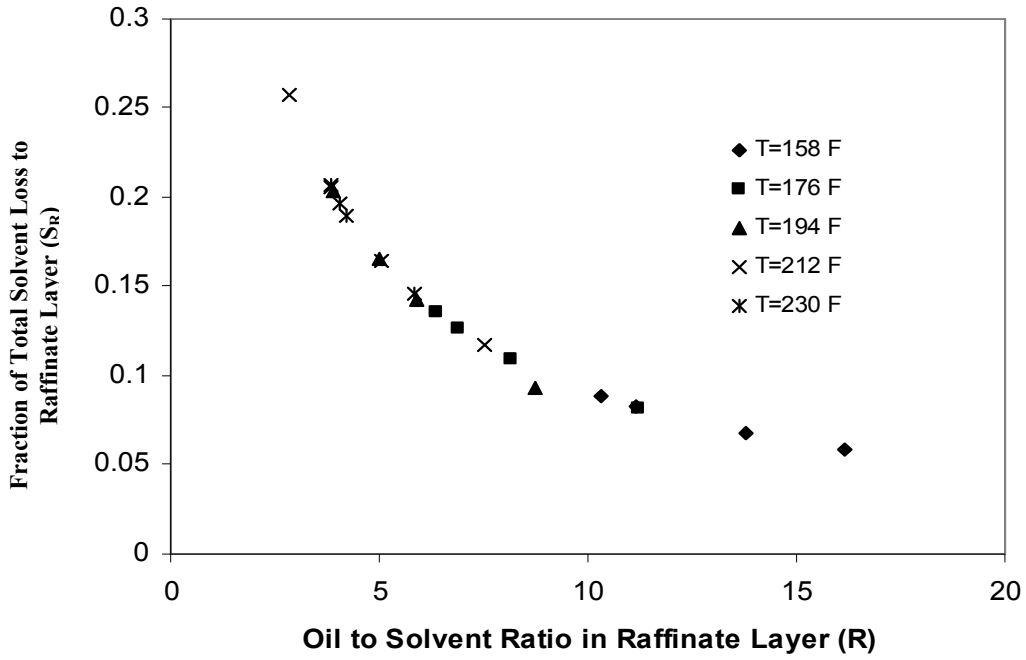


Fig.2. Effect of R on S_R in Extraction of Light Lube Oil by Furfural.

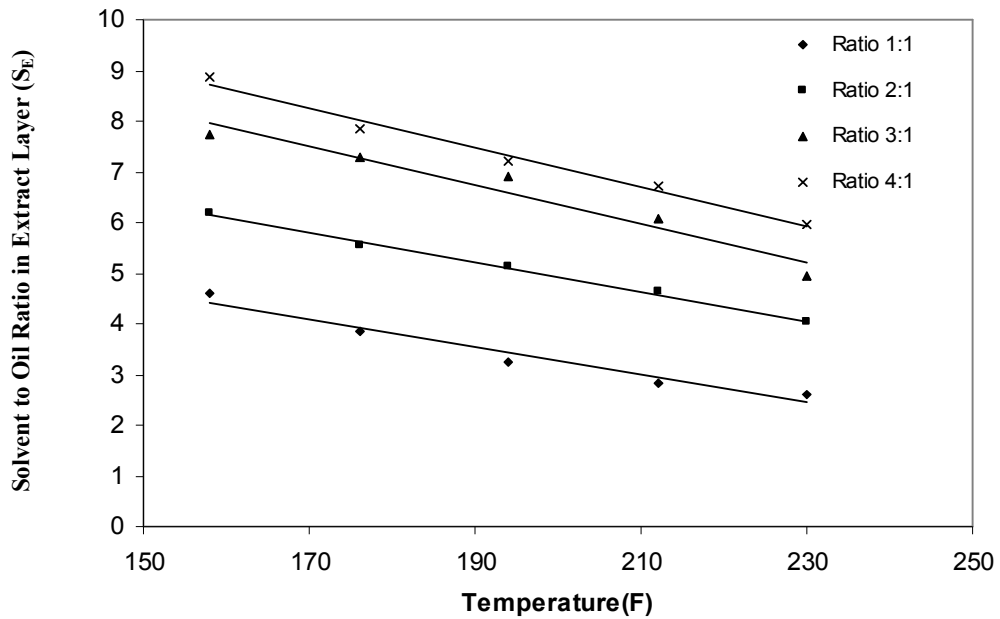


Fig.3. Effect of Temperature on the Solvent to Oil Ratio in Extract Layer.

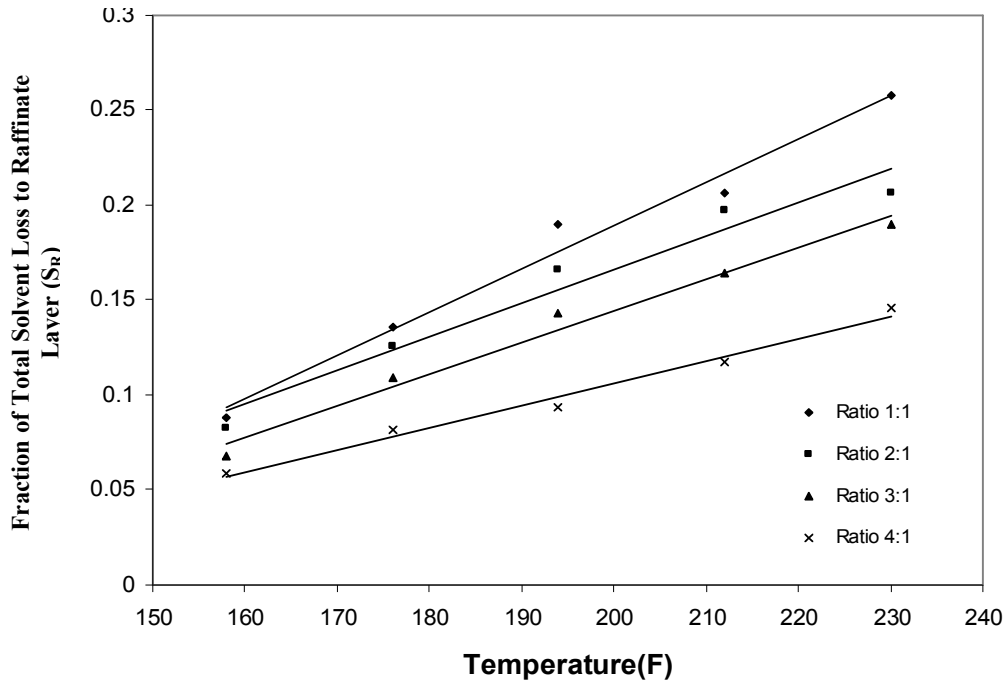


Fig.4. Effect of Temperature on the Fraction of Total Solvent in Raffinate Layer.

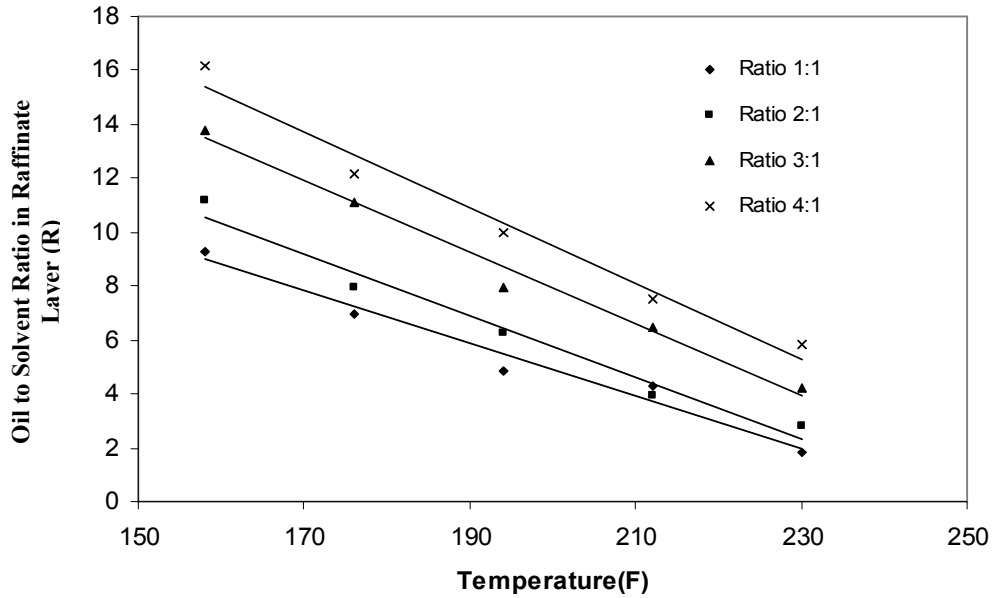


Fig.5. Effect of Temperature on the Oil to Solvent Ratio in Raffinate.

Specified regression is applied using the experimental results of extraction lube oil with furfural and that depends on Eqns.3-6 as estimated functions and Quasi-Newton estimation method[17]. This model is applied at optimum extraction temperature 212 °F and solvent charge to oil ratio 1-4. Figures 6 and 7 show the relations of predicted vs. observed extract yield values. There is a good similarity in 1:1 and 2:1 solvent charge to oil ratio; while there is some difference in 3:1 and 4:1. Figures 8 and 9 show predicted

versus observed fraction of total solvent loss to raffinate layer values. There is an excellent similarity in all range of solvent charge to oil ratio. All statistical values of applied empirical equations are tabulated in Table1. The statistical values and figures refer to the high representation of these selective equations to the extraction system where the predicted and observed values are so close. Equations 3-6 are good modeling function for prediction extraction data at various operating conditions.

**Table 1,
Statistical Values of Estimated Functions.**

	$\log E = 0.75 \log S_E - 2.1$	$\log E = (0.2 + 0.005^1 T) \log S_E + (0.14 - 0.02 T)$	$\log S_R = -0.82 \log R - 0.48$	$\log S_R = (0.19 - 0.01T) \log R + (0.14 - 0.006^1 T)$
σ (variance)	90.926%	90.926%	99.929%	99.929%
R (correlation factor)	0.954	0.953	0.999	0.999
Final loss	0.026	0.026	0.0002	0.0002

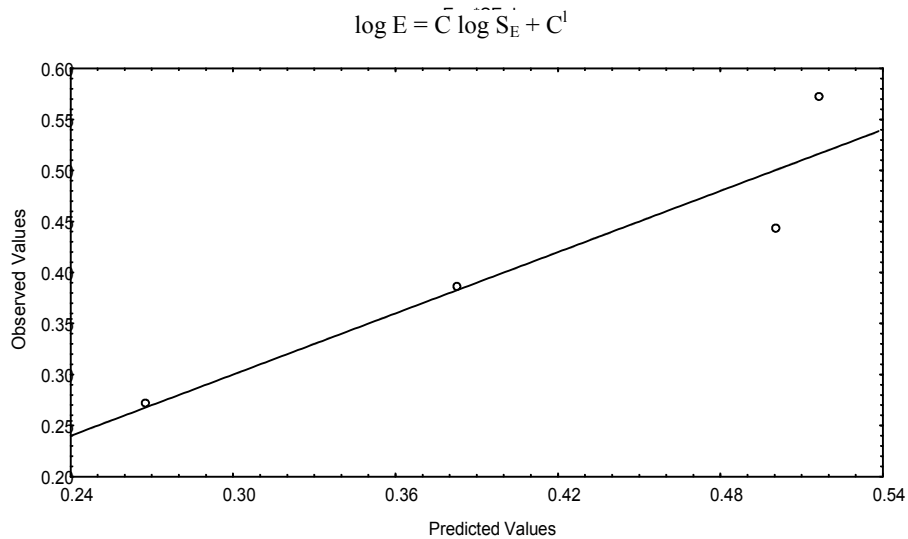


Fig.6. Predicted vs. Observed Extract Yield Values of Extraction Lube Oil with Furfural.

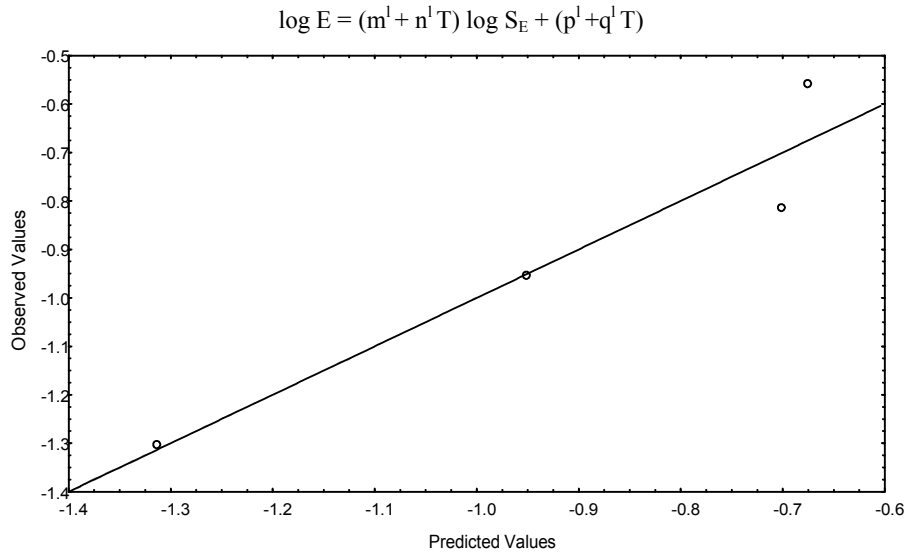


Fig.7. Predicted vs. Observed Extract Yield Values of Extraction Lube Oil with Furfural.

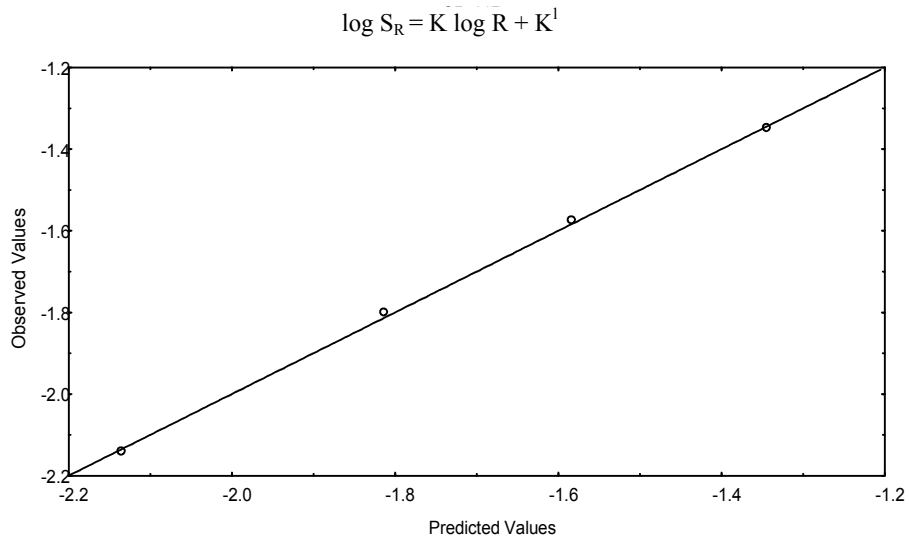


Fig.8. Predicted vs. Observed Fraction of Total Solvent Loss to Raffinate Layer Values of Extraction Lube Oil with Furfural.

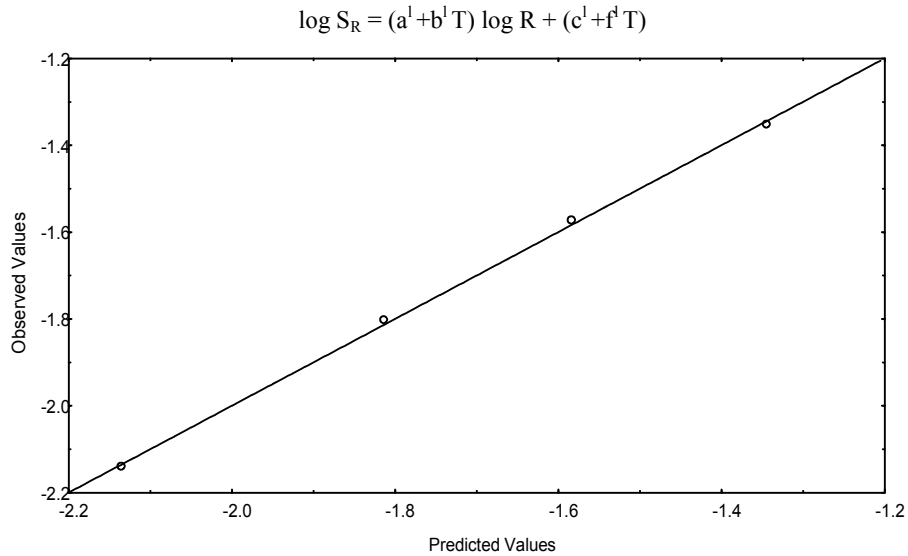


Fig.9. Predicted vs. Observed Fraction of Total Solvent Loss to Raffinate Layer Values of Extraction Lube Oil with Furfural.

3. Mass Transfer Coefficient in Mixer-settler

Mass transfer coefficient of continuous phase is calculated from Eqn.7 as follows:

$$k_c d_T / D_c = 0.052 (d_R^2 N \rho_c / \mu_c)^{0.833} (\mu_c / \rho_c D_c)^{0.5} \dots(7)$$

Physical properties such as density and viscosity of mixture are calculated from Eqns.9&10:

$$\rho_m = x \rho_d + (1-x) \rho_c \dots(9)$$

$$\mu_m = (\mu_c / 1-x)(1 + (6x \mu_d / \mu_c + \mu_d)) \dots(10)$$

Diffusivity coefficients of solute in the continuous and dispersed phase are calculated from Eqn.11[18, 19]

$$D = 9.96 * 10^{-16} T / \mu (V)^{1/3} \dots(11)$$

Mass transfer coefficient of dispersed phase is calculated from Eqn.12[20]:

$$k_d = 17.9 D_d / d_{vs} \dots(12)$$

The volume surface diameter of drops d_{vs} is calculated from Eqn.13:

$$d_{vs} = 6x/a \dots(13)$$

Where a is calculated from Eqn.14[21]:

$$a = 25.9 (N_{we})^{0.5} (N_{Re})^{0.1} (x)^{0.84} / d_R \dots(14)$$

Figures 10 and 11 show the effect of temperature on the mass transfer coefficient of continuous phase k_c and dispersed phase k_d respectively. Mass transfer coefficients of continuous and dispersed phase are increased with increasing temperature and solvent to charge oil ratio. The reason of this temperature effect is that mass transfer coefficient is directly proportional directly and a function of diffusivity which is proportional with temperature increase which necessarily leads to the increase of mass transfer coefficients. The inverse proportion of mass transfer coefficient with viscosity and density decreased with increasing temperature. On the other hand the increase of mass transfer coefficient of dispersed phase with increasing solvent to charge oil ratio at constant temperature caused by the effect of dispersed phase holds up on the interfacial area of drops and then on mean drop size that necessarily has an effect on mass transfer coefficient of dispersed phase. It is noted that the interfacial area of drops decreased with increasing solvent to charge oil ratio (or decreasing dispersed phase hold up) and this caused the mean drop size the decrease, and mass transfer coefficient of dispersed phase to increase in addition to the effect of dispersed phase hold up on density of mixture and in other word on Weber number. Also Mass transfer coefficient of continuous phase increased with increasing solvent to charge oil ratio because the effect of

hold up of dispersed phase on viscosity of mixture decreased with decreasing hold up at constant temperature that lead to the increasing of mass transfer coefficient of continuous phase.

The overall mass transfer coefficient extraction of light lube oil distillate fraction by furfural is calculated from Eqn.15:

$$1/K_{od} = m/k_c + 1/k_d \quad \dots(15)$$

Figure 12 shows the effect of temperature on the overall mass transfer coefficient K_{od} which increases with increasing temperature and solvent to charge oil ratio; while in Figure 13 ($K_{od} \cdot a$) increases with temperature and decreases with solvent charge to oil ratio.

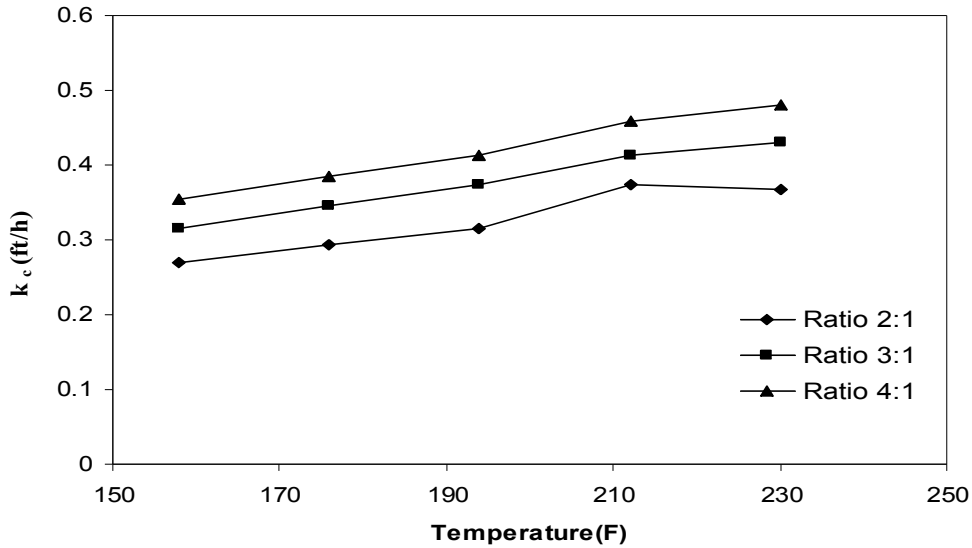


Fig.10. Effect of Temperature on Mass Transfer Coefficient of Continuous Phase Extraction of Light Lube Oil by Furfural.

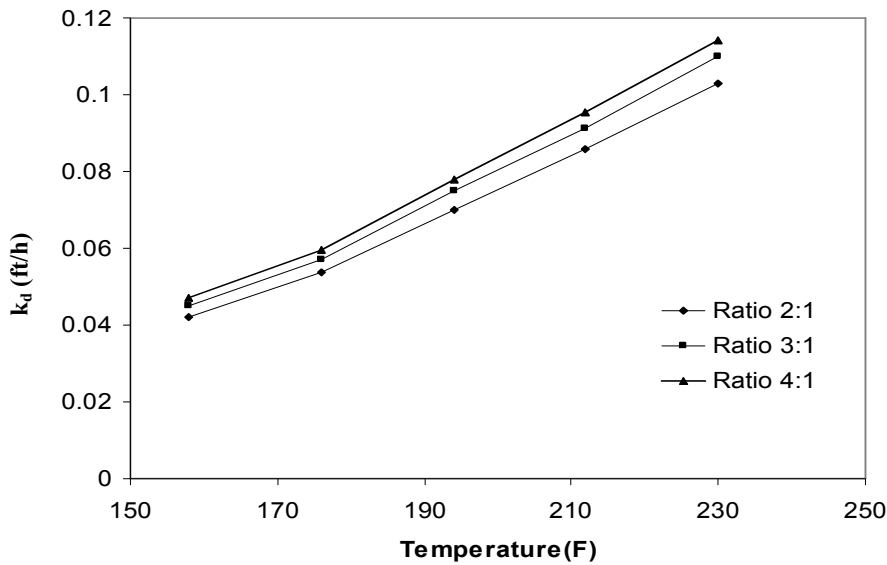


Fig.11. Effect of Temperature on Mass Transfer Coefficient of Dispersed Phase Extraction of Light Lube Oil by Furfural.

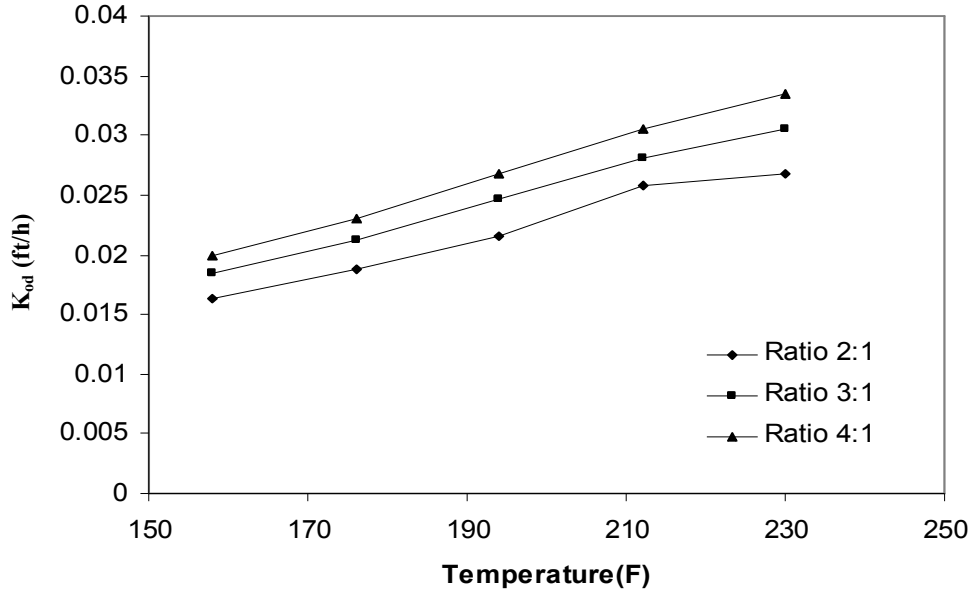


Fig.12. Effect of Temperature on the Over All Mass Transfer Coefficient Extraction of Light Lube Oil by Furfural.

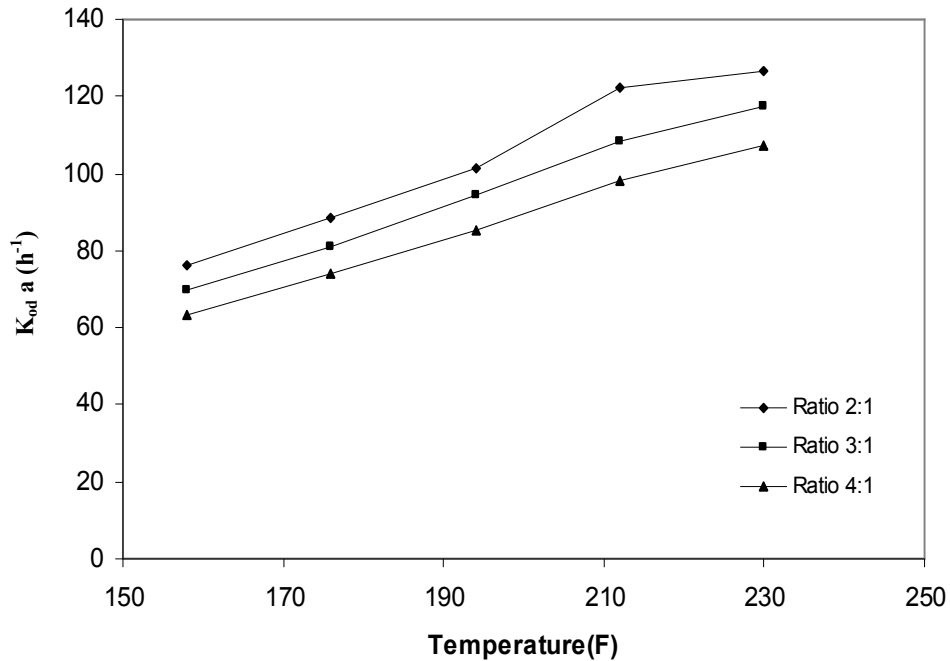


Fig.13. Effect of Temperature on the Over All Mass Transfer Coefficient Extraction of Light Lube Oil by Furfural.

4. Conclusions

1. Mathematical analysis of solvent extraction equilibria shows that the extraction yield and fraction of total solvent loss to raffinate at constant temperature extraction may be expressed by equation 3 & 4; while assuming temperature effect similar to that found by Kalichevsky, the extraction yield and fraction of total solvent loss to raffinate may be expressed by equation 5 & 6. Equations 3-6 are good predicting function for extraction data at various operating conditions.
2. Operating conditions have a significance effect on the mass transfer coefficient of continuous and dispersed phase which increased with increasing temperature and solvent to charge oil ratio.
3. The overall mass transfer coefficients K_{od} and $K_{od} \cdot a$ are related directly with temperature. They increases with increasing temperature but they differ in their response to solvent to charge oil ratio where K_{od} is increased and $K_{od} \cdot a$ is decreased.

Nomenclature

a	Interfacial area of drop ft^2/ft^3
D	Diffusivity, m^2/s
D_c	Diffusivity of solute in the continuous phase, ft^2/h
D_d	Diffusivity of solute in the dispersed phase, ft^2/h
d_R	Diameter of rotor, ft
d_T	Vessel diameter, ft
d_{vs}	Volume surface diameter of drops, ft
E	Extract yield
k_c	Individual mass transfer coefficient of continuous phase, ft/h
k_d	Individual mass transfer coefficient of dispersed phase, ft/h
$K_{od} a$	Over all mass transfer coefficient based on dispersed phase, h^{-1}
M	Equilibrium distribution coefficient
N	Speed of rotor, rph
P	Power consumption. $ft \text{ Ib}_f / \text{min}$
R	Ratio of Oil to solvent in raffinate phase

S	Solvent to charge oil ratio
S_E	Ratio of solvent to oil in extract phase
S_R	Fraction of total solvent in raffinate phase
T	Temperature, K
V	Solute molar volume, $m^3/g \text{ mol}$
v	Volume of mixing vessel, ft^3
x	Holdup of the dispersed phase
$a_1, b, a^1, b^1,$ $C, C^1, c^1, c,$ $f, K, K^1, m,$ $n, m^1, n^1, p,$ $p^1, q, q^1,$	Constants

Greek Symbols

ρ_c	Density of continuous phase, Ib/ft^3
ρ_m	Density of mixed phase, Ib/ft^3
ρ_d	Density of dispersed phase, Ib/ft^3
μ	Viscosity of mixed phase, Pa.s
μ_c	Viscosity of continuous phase, $Ib/ft \text{ h}$
μ_m	Viscosity of mixed phase, $Ib/ft \text{ h}$

5. References

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تخمين ناتج الاستخلاص و معامل انتقال المادة في عملية الاستخلاص بالمذيب لزيت التزييت

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الخلاصة

تناول هذا البحث ايجاد علاقات لحساب الناتج والخواص لمقطع زيت التزييت الخفيف المحسن من عملية الاستخلاص بالفرفور الهاس تخدام موديلات تجاهلية انتقال المادة في نظام الخلط والفصل تم حساب معامل انتقال المادة في الطور المستمر ومعامل انتقال المادة في الطور المشدنت ومعامل انتقال المادة الكلي لعملية الاستخلاص لمقطع زيت التزييت الخفيف واسطة الفرفورال بالاضافة الى كل الخواص الفيزيائية للمركبات كل على حده و خلاط نظام الاستخلاص . تم دراسة المتغيرات المؤثرة على عملية الاستخلاص والتي هي درجة حرارة الاستخلاص وتتراوح من ٧٠ الى ١٠٠م، والمتغير الأخر هو نسبة المذيب الى الزيت وتتراوح من ١:١ الى ١:٤ .

اظهرت نتائج هذا البحث بان ناتج الاستخلاص يقل بنقصان نسبة المذيب الى زيت التزييت في طبقة المستخلص ويزداد بزيادة درجة الحرارة . إن نسبة المذيب الكلي في طور الراقينت يقل بزيادة نسبة زيت التزييت الى المذيب في طبقة الراقينت ويزداد بزيادة درجة الحرارة نسبة المذيب الى الزيت في طور الاستخلاص يقل بزيادة درجة الحرارة ويزداد بزيادة نسبة المذيب الى زيت التزييت اللقيم بثبوت درجة الحرارة في الراقينت يقل بزيادة درجة الحرارة ويزداد بزيادة نسبة المذيب الى زيت التزييت اللقيم بثبوت درجة الحرارة .

ان الدوال الرياضية التي تم اقتراحها هي تعتبر من افضل الموديلات الرياضية لتمثيل نظام الاستخلاص هذا بمختلف الظروف التشغيلية . يزداد معامل انتقال المادة في الطور المستمر ومعامل انتقال المادة في الطور المشدنت بزيادة درجة الحرارة ونسبة المذيب الى زيت التزييت اللقيم بثبوت درجة الحرارة . يزداد معامل انتقال المادة الكلي بزيادة درجة الحرارة ونسبة المذيب الى زيت التزييت اللقيم بينما يزداد K_{od} بزيادة درجة الحرارة ويقل بزيادة نسبة المذيب الى زيت التزييت اللقيم .