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Solubility and thermodynamic parameters of a novel anti-cancer drug (DHP-5) in polyethylene glycol 400 + water mixtures

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ABSTRACT

Solubility of dihydropyrimidine derivative *4-(4-ethoxyphenyl)-5-(3,4,5 trimethoxybenzoyl)-3,4-dihydropyrimidine-2(1H) one (DHP-5)*, a novel anticancer drug, was experimentally measured in PEG-400 + water binary solvent mixtures over a temperatures range from 298.15 to 318.15 K. Thermodynamic parameters including enthalpy, entropy and Gibbs free energy of the solubility data were calculated using van't Hoff equation. Experimental solubility data was employed to evaluate the relative performance of a number of models including van't Hoff, Apelblat, Yalkowsky and Jouyban–Acree models for their prediction efficacy. The Jouyban–Acree model covering both solvent composition and temperature effects on drug's solubility proved to be superior to the other three models for its prediction accuracy.

1. Introduction

There are many parameters involved in the assessment of the suitable drug candidate. Intestinal drug absorption is a critical factor which can limit drug potency and bioavailability. Aqueous solubility is a key parameter to help determine rate and extent of drug absorption. Currently majority of the newly established drugs in the market suffer from low aqueous solubility. This can compromise drug absorption and thus influence its efficacy. Various techniques are employed to increase the dissolution rate or solubility of poorly water soluble drugs. Co-solvency, micellization and drug inclusion are some of the widely used strategies to increase solubility of drug molecules [1–4].

A dihydropyrimidine derivative *4-(4-ethoxyphenyl)-5-(3,4,5 trimethoxybenzoyl)-3,4-dihydropyrimidine-2(1H) one* coded as DHP-5 is a novel compound with great antitumor activities against many cancer cells including breast and colon. Due to its low aqueous solubility formulation development of this compound is limited. Its solubility in various mono-solvents at different temperatures has been studied [5].

Over the past decade, different approaches have been used to develop reliable models to predict or correlate solubility of drug molecules. Various linear and non-linear regression models have been trained and compared for their reliability in solubility prediction. The Apelblat model correlates drug solubility as a function of temperature. Yalkowsky presented a simple linear model to predict solubility in various binary solvent mixtures. Due to the limitations of the presented models, several other equations were developed with more prediction accuracy and less deviation from the experimental data. Some of these models include Jouyban–Acree model and the extended Hildebrand solubility approach and were reviewed [6]. The Jouyban–Acree model has been employed for the prediction of drug solubility, density, viscosity and surface tension of mixed solvents [7–10].

Polyethylene glycol 400 (PEG 400) is one of the pharmaceutical cosolvents used in many marketed drug formulations. The solubility of drugs could be enhanced by adding PEG 400 alone or in combination with other solubilizing agents. In addition to the data sets of various drugs in PEG 400 + water mixtures compiled in a published handbook [11], the solubilities of pioglitazone HCl [12,13], acetaminophen and ibuprofen [14], satanidazole [15], lamotrigine [16,17], ranitidine HCl [18], indomethacine [19], diazepam [20], tadalafil [21], N-(4-chlorophenyl)-2-(pyridin-4-ylcarbonyl) hydrazine carbothioamide (isoniazid analogue) [22], flofenicol [23], deferiprone [24], glibenclamide [25], clonazepam [26], fluphenazine decanoate [27], naproxen [28], (2Z)-N-cyclohexyl-2-(3-hydroxybenzylidine) hydrazine carbothioamide [29], piroxicam [30], meloxicam [31], isatin [32], silymarin [33], tenoxicam [34], lornoxicam

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[35], sulfadiazine [36] and celexocib [37] in PEG 400 mixtures with water or organic solvents have been reported in the literature.

The aim of the present work is to study the effect of co-solvency and to measure mole fraction solubility of DHP-5 in PEG 400 + water mixtures at various temperatures and determine the thermodynamic parameters of the dissolution process including enthalpy, entropy and Gibbs free energy using the van't Hoff equation. We also aimed to apply four various models including Yalkowsky, Apelblat, van't Hoff and Jouyban–Acree to the experimentally obtained solubility data set and to compare the relative performance of all modeling methods.

2. Experimental

2.1. Materials and methods

DHP-5 was chemically synthesized and characterized in the pharmaceutical chemistry Laboratory, College of Pharmacy of King Saud University, Riyadh, Saudi Arabia. PEG-400 was obtained from "Fluka Chemica (Buchs, Switzerland)". HPLC grade methanol and ethanol were purchased from "Sharlau Chemie (Spain)". Double distilled water was obtained from Milli-Q.

2.2. Solubility measurements

Mole fraction solubility of DHP-5 was measured using the Higuchi and Connor's shake flask method [38]. Briefly, an excess amount of DHP-5 was mixed in PEG 400 + water mixtures (mass fraction $m_1 = 0.1–0.9$) including neat water ($m_1 = 0.0$) and neat PEG 400 ($m_1 = 1.0$). Co-solvent systems were allowed to equilibrate in a biological shaker (Julabo, PA) at 100 rpm for 3 days at atmospheric pressure of 0.1 MPa. Samples were then allowed to settle solid DHP-5 particles and the supernatants were taken, diluted and quantified using HPLC method. All experiments were carried out in triplicates.

2.3. DHP-5 quantification

DHP-5 was quantified by reverse phase high performance liquid chromatography (HPLC) from "Waters, USA". Analysis was carried out using a "Nucleodur RP C_8 column (5 μm packing, 150 mm × 4.6 mm)" with a UV detection at 300 nm. Ethanol:methanol (50:50% v/v) was utilized as the mobile phase with a flow rate of 1 ml/min at 298.15 K; volume of injection 10 μl gave a linear calibration curve with a $R^2 = 0.999$ at the concentration range of 1–100 μg/g.

2.4. Thermodynamic analysis

The thermodynamic analysis of DHP-5 was studied through solution enthalpy and entropy changes of van't Hoff equation. Thermodynamic changes of the solutions are obtained at mean harmonic temperature, T_{hm}, defined as:

$$T_{hm} = n/\sum_{i=1}^{n}(1/T) \tag{1}$$

where n is the number of temperatures analyzed [39].

The modified van't Hoff expression was used to relate logarithm of mole fraction solubility of DHP-5 (ln X) to the reciprocal of the temperature to calculate standard enthalpy of the solute (ΔH^o_{sol}) [39,40]:

$$\left(\frac{\partial \ln X}{\partial\left(\frac{1}{T}-\frac{1}{T_{hm}}\right)}\right)_p = -\frac{\Delta H^o_{sol}}{R} \tag{2}$$

where T is the absolute temperature (K) and R is the universal gas constant (=8.314 J/mol K).

The standard solution enthalpies ΔH^o_{sol}were calculated using equation [39,40]:

$$d(\ln X)/dT = \Delta H^o_{sol}/RT^2. \tag{3}$$

The Gibbs free energy of DHP-5 dissolution, ΔG^o_{sol}, was determined from the intercept of the above equation using the approach [39,40]:

$$\Delta G^o_{sol} = -RT_{hm}\tilde{n}\text{intercept}. \tag{4}$$

Dissolution entropy ΔS^o_{sol}, is obtained as [39,40]:

$$\Delta S^o_{sol} = \frac{(\Delta H^o_{sol} - \Delta G^o_{sol})}{T_{hm}}. \tag{5}$$

2.5. Computational validation

2.5.1. van't Hoff model

The van't Hoff equation relates the logarithm of drug solubility as a function of $1/T$ by the ideal solution given by [41]:

$$\ln X_T = a + \frac{b}{T} \tag{6}$$

where X_T presents mole fraction solubility of DHP-5, a and b are the model constants [41].

2.5.2. Apelblat model

The Apelblat model was used to correlate the experimentally obtained solubility data in a temperature dependent manner [42]:

$$\ln X_T = A + \frac{B}{T} + C\ \ln T \tag{7}$$

where X_T presents mole fraction solubility of DHP-5, and A, B and C are the model constants.

2.5.3. Yalkowsky model

The original version of the log-linear model of Yalkowsky employs volume fractions of the solvents and drug molar solubility in the mono-solvents to correlate experimental molar solubilites of drugs at room temperature. It is possible to use mass fractions instead of volume fractions of the solvents to represent the solubility of DPH-5 in PEG 400 + water mixtures (X_m) at room temperature as [43]:

$$\ln X_T = m_1\ \ln X_1 + m_2\ \ln X_2 \tag{8}$$

where m_1 and m_2 are mass fractions of solvents 1 and 2, X_1 and X_2 represent drug solubility in neat water and PEG 400, respectively. To extend the applicability of the model to various temperatures, its combination with the van't Hoff model could be considered as:

$$\ln X_{m,T} = m_1\left(A_1 + \frac{B_1}{T}\right) + m_2\left(A_2 + \frac{B_2}{T}\right). \tag{9}$$

2.5.4. Jouyban–Acree model

The Jouyban–Acree model representing for solute solubility in binary solvent mixtures at various temperatures is expressed as:

$$\ln X_{m,T} = m_1\ \ln X_{1,T} + m_2\ \ln X_{2,T} + m_1 m_2 \sum_{i=0}^{2}\frac{J_i}{T}(m_1 - m_2)^i \tag{10}$$

in which J_i denotes the constants of the model computed by a no intercept regression analysis [9,44]. Combining the Jouyban– Acree

model and van't Hoff model (Eq. (6) provide more comprehensive computations) [9] as:

$$\ln X_{m,T} = m_1\left(A_1 + \frac{B_1}{T}\right) + m_2\left(A_2 + \frac{B_2}{T}\right) + m_1 m_2 \sum_{i=0}^{2} \frac{J_i}{T}(m_1 - m_2)^i. \quad (11)$$

To evaluate the accuracy of model predictions, the discrepancy between the calculated and the experimentally measured values was computed using the mean percentage deviation (MPD) presented as:

$$MPD = \frac{100}{ND}\sum\left(\frac{\left|X^{cal} - X^{\exp}\right|}{X^{\exp}}\right) \quad (12)$$

where *ND* denotes the number of experimental data points in each set.

3. Results

3.1. Experimental solubility

Experimental mole fraction solubility of DHP-5 in PEG 400 + water mixtures at five different temperatures is listed in Table 1. Drug solubility increased with the raise in temperature. The lowest mole fraction solubility was observed in aqueous solution at 298.15 K (8.04×10^{-6}) and the highest solubility was observed in neat PEG 400 at 318.15 K (1.22×10^{-2}). Drug solubility showed an increase with increase in the mass fraction of PEG 400. Mole fraction solubility may depend on factors such as solvent polarity and chemical structure. High drug solubility observed here might be due to the low dielectric constant of PEG 400 as compared to that of water [45]. DHP-5 solubility in 12 various pure solvents has been studied by our group. The highest solubility was observed in PEG 400 (1.22×10^{-2}) followed by DMSO (9.96×10^{-3}) at 318.15 K [5].

3.2. Thermodynamic analysis

Thermodynamic parameters computed from generated solubility data are listed in Table 2. ΔH^o_{sol} value for DHP-5 in all solvent compositions was recorded as positive and in neat water and neat PEG 400 were found to be 31.1 and 46.4 kJ mol^{-1}, respectively. From Table 2, it can be seen that ΔH^o_{sol} showed a linear increase from neat water to neat PEG 400. The higher value for PEG 400 is probably due to the stronger molecular interaction between drug and the solvent. This corresponds to the high solubility of DHP-5 in neat PEG 400. The highest ΔS^o_{sol} values for DHP-5 dissolution were observed in neat PEG 400 at 70.8 J K^{-1} mol^{-1} while the lowest value was observed in neat water at 58.2 J K^{-1} mol^{-1}. The positive value of ΔH^o_{sol} and ΔS^o_{sol} indicates an endothermic and entropy-driven dissolution of DHP-5 in PEG 400 + water mixtures.

Table 2
Apparent thermodynamic quantities ($\Delta_{sol}H^0$, $\Delta_{sol}G^0$ and $\Delta_{sol}S^0$) and R^2 values for dissolution of DHP-5 in in various PEG 400 (1) + water (2) mixtures[a].

m_1	$\Delta_{sol}H^0$/kJ mol^{-1}	$\Delta_{sol}G^0$/kJ mol^{-1}	$\Delta_{sol}S^0$/J mol^{-1} K^{-1}	R^2
0.0	46.4	28.4	58.2	0.998
0.1	44.3	26.8	56.7	0.997
0.2	43.5	25.2	59.3	0.998
0.3	44.2	23.5	67.1	0.995
0.4	40.4	21.9	59.9	0.997
0.5	39.8	20.3	63.4	0.997
0.6	39.6	18.7	67.7	0.999
0.7	37.8	17.1	67.4	0.993
0.8	36.4	15.5	68.1	0.995
0.9	34.8	13.8	68.0	0.996
1.0	34.1	12.3	70.8	0.995

[a] The relative uncertainties are $u(\Delta_{sol}H^0) = 0.24$ kJ mol^{-1}, $u(\Delta_{sol}G^0) = 0.25$ kJ mol^{-1} and $u(\Delta_{sol}S^0) = 0.58$ J mol^{-1} K^{-1}.

The positive value for ΔG° in neat PEG 400 and water was 12.3 and 28.4 kJ mol^{-1} respectively. The ΔG° value was found to decrease with increasing mass fraction of PEG 400. The low ΔG° value in neat PEG 400 corresponds to higher DHP-5 dissolution. These results are in accordance with the solubility data of DHP-5 in co-solvent mixtures.

3.3. Computational results

3.3.1. van't Hoff model

In order to illustrate the performance of the van't Hoff equation on DHP-5 solubility, 55 experimental data points were fitted to the van't Hoff model and 11 trained models were obtained and then compared using MPD values in which the results are presented in Table 3. The MPD values in all samples were recorded as 1.1 to 2.7% with the overall value of 2.0%. R^2 value was in the range of 0.992 to 0.998. These results show good correlations between the experimental data and predicted values of van't Hoff model.

3.3.2. Apelblat model

The experimentally obtained solubility data were fitted to Eq. (7) and model parameter A, B and C were computed by multivariate regression analyses and the values are presented in Table 4. The experimental and predicted solubility data and the MPD values are shown in Table 4. Results of MPD were in the range of 1.5 to 2.8% with the overall MPD of 2.3%. Due to the good linearity of the generated data, the B terms are not statistically significant, therefore Apelblat model reduces to the Hildebrand model. This model show good accuracy with R^2 values in the range of 0.991 to 0.997.

Table 1
The mole fraction solubilities (*X*) of DHP-5 in various PEG 400 (1) + water (2) mixtures at temperatures $T = (298.15$ to $318.15)$ K and pressure $p = 0.1$ MPa[a].

	X				
m_1	$T = 298.15$ K	$T = 303.15$ K	$T = 308.15$ K	$T = 313.15$ K	$T = 318.15$ K
0.0	8.04×10^{-6}	1.11×10^{-5}	1.52×10^{-5}	2.04×10^{-5}	2.57×10^{-5}
0.1	1.57×10^{-5}	2.10×10^{-5}	2.86×10^{-5}	3.84×10^{-5}	4.73×10^{-5}
0.2	2.96×10^{-5}	4.05×10^{-5}	5.39×10^{-5}	7.13×10^{-5}	8.86×10^{-5}
0.3	5.61×10^{-5}	7.65×10^{-5}	1.06×10^{-4}	1.39×10^{-4}	1.69×10^{-4}
0.4	1.10×10^{-4}	1.51×10^{-4}	1.95×10^{-4}	2.50×10^{-4}	3.08×10^{-4}
0.5	2.06×10^{-4}	2.78×10^{-4}	3.58×10^{-4}	4.65×10^{-4}	5.63×10^{-4}
0.6	3.92×10^{-4}	5.26×10^{-4}	6.69×10^{-4}	8.63×10^{-4}	1.07×10^{-3}
0.7	7.44×10^{-4}	1.02×10^{-3}	1.27×10^{-3}	1.64×10^{-3}	1.95×10^{-3}
0.8	1.43×10^{-3}	1.90×10^{-3}	2.40×10^{-3}	3.05×10^{-3}	3.60×10^{-3}
0.9	2.74×10^{-3}	3.62×10^{-3}	4.49×10^{-3}	5.63×10^{-3}	6.64×10^{-3}
1.0	5.13×10^{-3}	6.78×10^{-3}	8.30×10^{-3}	1.04×10^{-2}	1.22×10^{-2}

[a] The standard uncertainties *u* are $u(T) = 0.13$ K, $u(p) = 0.003$ MPa and $u_r(X) = 1.3\%$.

Table 3
van't Hoff model parameters (a and b), R^2 and *MPD* for DHP-5 in various PEG 400 (1) + water (2) mixtures.

m_1	a	b	R^2	MPD
0.0	6.961	−5568.785	0.997	1.6
0.1	6.834	−5333.804	0.997	1.8
0.2	7.157	−5237.859	0.997	1.7
0.3	8.092	−5324.684	0.993	2.7
0.4	7.242	−4869.008	0.996	2.0
0.5	7.619	−4796.065	0.998	1.9
0.6	8.112	−4752.743	0.992	1.1
0.7	8.135	−4563.559	0.992	2.5
0.8	8.256	−4407.132	0.994	2.2
0.9	8.220	−4202.112	0.994	2.1
1.0	8.521	−4104.494	0.993	2.1
			Overall	2.0

3.3.3. Yalkowsky model

The classical version of the Yalkowsky model was originally developed for representing the solubility data at room temperature. As noted above, a combination of van't Hoff and Yalkowsky models could be presented as:

$$\ln X_{m,T} = m_1\left(8.540 - \frac{4106.435}{T}\right) + m_2\left(6.941 - \frac{5559.064}{T}\right) \quad (13)$$

which correlate the experimental data of DHP-5 in various solvent compositions at different temperatures with MPD values in the range of 1.4 to 2.7% and the overall MPD of 2.0% (for details see Table 5). The main advantage of this trained version to the classical version of Yalkowsky model is that it does not require any further experimental data to predict the solubility of DHP-5 in other solvent compositions or temperatures of interest.

3.3.4. Jouyban–Acree model

Performance of the Jouyban–Acree model and its combined version with van't Hoff equation were studied. The solubility data was fitted to Eqs. (10) and (11), then the model constants were computed using least square analyses resulting in trained equations to represent whole data points as:

$$\ln X_{m,T} = m_1.\ \ln X_{1,T} + m_2.\ \ln X_{2,T} + \frac{25.114 m_1.m_2}{T} \quad (14)$$

and

$$\ln X_{m,T} = m_1.\left(8.540 - \frac{4109.943}{T}\right) + m_2.\left(6.941 - \frac{5562.572}{T}\right) + \frac{23.385 m_1.m_2}{T}. \quad (15)$$

Table 4
Apelblat parameters (A, B and C), R^2 and *MPD* for DHP-5 in various PEG 400 (1) + water (2) mixtures.

m_1	A	B	C	R^2	*MPD*
0.0	−114.710	NS[a]	18.077	0.997	2.0
0.1	−109.707	NS	17.315	0.996	2.0
0.2	−107.281	NS	17.003	0.996	2.0
0.3	−108.220	NS	17.281	0.991	3.0
0.4	−99.126	NS	15.803	0.994	2.3
0.5	−97.159	NS	15.567	0.995	2.2
0.6	−95.737	NS	15.430	0.997	1.5
0.7	−91.549	NS	14.810	0.990	2.8
0.8	−88.014	NS	14.303	0.992	2.5
0.9	−83.573	NS	13.638	0.992	2.4
1.0	−81.138	NS	13.321	0.991	2.4
				Overall	2.3

[a] NS: Not significant.

Table 5
Logarithmic solubilities (ln$X$) of DHP-5 calculated by an extended version of Yalkowsky model in PEG-400 (1) + water (2) mixtures at T = (298.15 to 318.15) K.

	ln X				
m_1	298.15	303.15	308.15	313.15	318.15
0.1	−11.06	−10.76	−10.47	−10.19	−9.92
0.2	−10.41	−10.12	−9.84	−9.56	−9.30
0.3	−9.76	−9.48	−9.21	−8.94	−8.68
0.4	−9.12	−8.84	−8.57	−8.32	−8.07
0.5	−8.47	−8.20	−7.94	−7.69	−7.45
0.6	−7.82	−7.56	−7.31	−7.07	−6.83
0.7	−7.17	−6.92	−6.68	−6.44	−6.22
0.8	−6.53	−6.28	−6.05	−5.82	−5.60
0.9	−5.88	−5.64	−5.42	−5.20	−4.98
MPD	2.1	1.7	1.4	2.2	2.7
Overall MPD			2.0		

These equations back-calculate the solubility of DHP-5 with the MPD of 0.8 and 2.0%, respectively. The Jouyban–Acree model proved to be superior to the other three models. Jouyban–Acree model is a versatile model that provides better predictability power over broader temperature range and solvent composition [39,46,47].

4. Conclusion

The solubility of DHP-5 in binary solvent mixtures of PEG 400 and water was studied. It was found that drug solubility increased with raise in temperature. Solubility increases with increase in PEG 400 mass fraction and the highest solubility was found in neat PEG 400. The apparent thermodynamic data present endothermic and entropy-driven dissolution of DHP-5 in all the investigated solvent mixtures. Different models were used to compare the relative performance of the obtained data set. The overall MPD values for the van't Hoff, Yalkowsky, Hildebrand, Jouyban–Acree model and its combined version with van't Hoff equation were 2.0, 2.0, 2.3, 0.8 and 2.0%, respectively.

Conflict of interest

"The authors state that they do not have any conflict of interest associated with this manuscript".

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References

[1] F. Shakeel, M.K. Anwer, G.A. Shazly, S. Jamil, J. Mol. Liq. 195 (2014) 255–258.
[2] F. Shakeel, N. Haq, M. El-Badry, F.K. Alanazi, I.A. Alsarra, J. Mol. Liq. 197 (2014) 334–338.
[3] A. Fathi Azarbayjani, S. Sajed-Amin, V. Panahi-Azar, K. Asadpour-Zeynali, A. Jouyban, Chem. Eng. Res. Des. 105 (2016) 64–70.
[4] A. Fathi Azarbayjani, H.S. Lin, C.W. Yap, Y.W. Chan, S.Y. Chan, J. Pharm. Pharmacol. 62 (2010) 770–778.
[5] F. Shakeel, M.A. Bhat, N. Haq, J. Mol. Liq. 220 (2016) 108–112.
[6] A. Jouyban, J. Pharm. Pharm. Sci. 11 (2008) 32–58.
[7] A. Jouyban, M. Khoubnasabjafari, Z. Vaez-Gharamaleki, W.E. Acree Jr., Chem. Pharm. Bull. 53 (2005) 519–523.
[8] A. Jouyban, S. Soltani, A. Fathi-Azarbaijani, W.E. Acree Jr., Anal. Methods 2 (2010) 1286–1297.
[9] A. Jouyban, M.A.A. Fakhree, W.E. Acree Jr., J. Chem. Eng. Data 57 (2012) 1344–1346.
[10] A. Jouyban, S.H. Maljaei, M. Khoubnasabjafari, Fathi-Azarbayjani, Indian J. Chem. 51 (2012) 695–698.
[11] A. Jouyban, Handbook of Solubility Data for Pharmaceuticals, CRC Press, Boca Raton, FL, 2010.
[12] A. Jouyban, S. Soltanpour, Chem. Pharm. Bull. 58 (2010) 1132–1135.
[13] A. Jouyban, S. Soltanpour, AAPS PharmSciTech 11 (2010) 1713–1717.
[14] A. Jouyban, S. Soltanpour, W.E. Acree Jr., J. Chem. Eng. Data 55 (2010) 5252–5257.
[15] P.B. Rathi, Iran J. Pharm. Res. 7 (2011) 17–24.

[16] A. Jouyban, S. Soltanpour, J. Mol. Liq. 180 (2013) 1–6.
[17] S. Soltanpour, A. Jouyban, Chem. Eng. Commun. 200 (2013) 1443–1456.
[18] J. Soleymani, D. Djozan, F. Martinez, A. Jouyban, J. Mol. Liq. 182 (2013) 91–94.
[19] F. Shakeel, F.K. Alanazi, I.A. Alsarra, N. Haq, J. Mol. Liq. 188 (2013) 28–32.
[20] S. Soltanpour, V. Panahi-Azar, A. Taheri, Z. Bastami, A. Jouyban, J. Solut. Chem. 42 (2013) 2281–2295.
[21] F. Shakeel, M. El-Badry, N. Haq, F.K. Alanazi, I.A. Alsarra, J. Drug Delivery Sci. Technol. 24 (2014) 539–542.
[22] M.A. Bhat, N. Haq, F. Shakeel, Thermochim. Acta 589 (2014) 235–240.
[23] J. Zhou, H. Fu, J. Peng, H. Cao, Y. Zhang, M. Lin, W. Wu, Z. Qing, J. Zhou, Fluid Phase Equilib. 376 (2014) 159–164.
[24] M. Abbasi, F. Martinez, A. Jouyban, J. Mol. Liq. 197 (2014) 171–175.
[25] S. Soltanpour, B. Jafari, M. Barzegar-Jalali, A. Jouyban, J. Drug Delivery Sci. Technol. 24 (2014) 111–115.
[26] Z. Bastami, S. Soltanpour, V. Panahi-Azar, A. Jouyban, J. Serb. Chem. Soc. 79 (2014) 445–456.
[27] A. Jouyban, F. Martinez, V. Panahi-Azar, Fluid Phase Equilib. 368 (2014) 58–64.
[28] S. Soltanpour, A.H. Shekarriz, Phys. Chem. Liq. 53 (2015) 748–762.
[29] F. Shakeel, M.A. Bhat, N. Haq, Thermochim. Acta 599 (2015) 52–56.
[30] S. Soltanpour, A. Garagozlu, J. Solut. Chem. 44 (2015) 1407–1423.
[31] Z.J. Cardenas, D.M. Jimenez, F. Martinez, J. Mol. Liq. 211 (2015) 233–238.
[32] F. Shakeel, N. Haq, F.K. Alanazi, I.A. Alsarra, J. Chem. Thermodyn. 82 (2015) 156–160.
[33] F. Shakeel, M.K. Anwer, Drug Dev. Ind. Pharm. 41 (2015) 1819–1823.
[34] F. Shakeel, N. Haq, F.K. Alanazi, I.A. Alsarra, J. Mol. Liq. 213 (2016) 221–227.
[35] F. Shakeel, N. Haq, F.K. Alanazi, I.A. Alsarra, J. Mol. Liq. 219 (2016) 439–443.
[36] D.M. Jimenez, Z.J. Cardenas, F. Martinez, J. Mol. Liq. 216 (2016) 239–245.
[37] S. Soltanpour, A. Mirzaei, J. Solut. Chem. 45 (2016) 1797–1810.
[38] T. Higuchi, K.A. Connors, Adv. Anal. Chem. Instrum. 4 (1965) 117–212.
[39] M.A.M. Ruidiaz, D.S.J. Rodríguez, R.P.C. Neita, B.D.M. Cristancho, R.F. Martínez, VITAE 17 (2010) 309–316.
[40] M.A. Fillippa, E.I. Gasull, J. Mol. Liq. 198 (2014) 78–83.
[41] D.J.W. Grant, M. Mehdizadeh, A.H.L. Chow, J.E. Fairbrother, Int. J. Pharm. 18 (1984) 25–38.
[42] A. Apelblat, E. Manzurola, J. Chem. Thermodyn. 31 (1999) 85–91.
[43] S.H. Yalkowsky, T.J. Roseman, Solubilization of drugs by cosolvents, in: S.H. Yalkowsky (Ed.), Techniques of Solubilization of Drugs, Marcel Dekker, New York, 1981.
[44] A. Jouyban-Gharamaleki, J. Hanaee, Int. J. Pharm. 154 (1997) 245–247.
[45] F. Shakeel, F.K. Alanazi, I.A. Alsarra, N. Haq, J. Mol. Liq. 191 (2014) 68–72.
[46] S.V. Patel, S. Patel, Eur. J. Pharm. Sci. 77 (2015) 161–169.
[47] L. Jiang, S. Li, J. Jiang, J. Qiu, Wan P, J. Mol. Liq. 211 (2015) 406–410.