Korean J. Chem. Eng., 38(7), 1487-1498 (2021)
DOI: 10.1007/s11814-021-0786-4

pISSN: 0256-1115
eISSN: 1975-7220

Spectroscopic and cloud point studies of the interaction and thermodynamics of ciprofloxacin hydrochloride+surfactants mixture in different solvents: Effect of temperature and composition

Md. Anamul Hoque[*,†], Md. Mofaqkharur Rahman[*], Shamim Mahbub[**], Mezbah Hossain[***], Mohammed Abdullah Khan[*], Md. Ruhul Amin[*,], Ali S. Alqahtani[****], Mohammad Z. Ahmed[****,†], Mohammed S. Alqahtani[*****], and Omar M. Almarfadi[****]**

*Department of Chemistry, Jahangirnagar University, Savar, Dhaka- 1342, Bangladesh
**Department of Chemistry & Physics, Gono Bishwabidyalay, Savar, Dhaka- 1344, Bangladesh
***Department of Chemistry, Hajee Mohammad Danesh Science & Technology University, Dinajpur- 5200, Bangladesh
****Department of Pharmacognosy, College of Pharmacy, King Saud University, PO Box 2457, Riyadh 11451, Saudi Arabia
*****Department of Pharmaceutics, College of Pharmacy, King Saud University, Riyadh 11451, Saudi Arabia
(*Received 22 June 2020 • Revised 8 March 2021 • Accepted 16 March 2021*)

Abstract−Surfactant is one of the most important chemical entities in drug formulation which can bind with drug molecules. Herein, the binding interaction of ciprofloxacin hydrochloride (CFH) drug with two different surfactants (sodium dodecyl sulfate (SDS) and Triton X-100 (TX-100)) has been investigated through UV-Visible spectroscopic and cloud point measurement techniques at different conditions. The absorption spectrum of CFH was found to be dependent on presence of additives/temperature change. The binding constant (K_b) of CFH+SDS/CFH+TX-100 was found to be increased primarily, reached a maximum value and then decreased with the increase of temperature, except in water medium (pH=2.0) and 30% (v/v) methanol. The K_b values for CFH+SDS were found to be higher in the aqueous medium than almost all medium studied herein, while better binding was observed in the alcoholic medium in the case of the CFH+TX-100 system. The Gibbs free energy of binding (ΔG_b^o) for both CFH+SDS and CFH+TX-100 systems were attained negative in each case studied, inferring the spontaneous binding phenomenon. The cloud point (CP) value of CFH+TX-100 mixture was lessened in $ZnSO_4 \cdot 7H_2O$ solution and the CP values exhibited a gradual reduction through the upsurge of electrolyte concentration. The positive values of the Gibbs free energy of clouding indicated the nonspontaneous clouding phenomena. To disclose the interaction between drug and surfactant, other thermodynamic parameters, e.g., enthalpy (ΔH_b^o) and entropy (ΔS_b^o), different transfer energies as well as entropy-enthalpy compensation parameters of binding/clouding were evaluated and clarified with proper explanation.

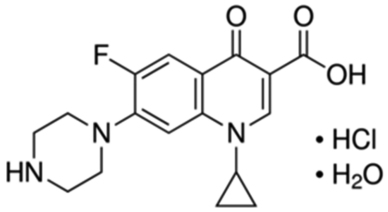
Keywords: Surfactant, Drug, Binding Constant, Thermodynamic Parameters

INTRODUCTION

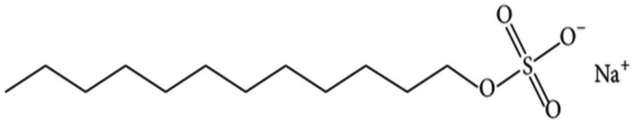
In pharmaceutical formulation, drug delivery, and drug release, solubility enhancer substances play a vital role. Most of the drug is hydrophobic, which needs to be absorbed in the aqueous systems of the human body, but lower aqueous solubility of the drugs causes lower bioavailability. Surfactants are exclusively utilized in the formulation of drug, which increases the solubility of the drug, consequently increases the bioavailability of the drugs [1]. Surfactants lessen the surface/interfacial tension of the water, which augments the aqueous solubility of the drugs. Again, the self-assembled structure (micelle) formation is another important property of the surfactants. The interaction of hydrophilic and hydrophobic portion of the surfactant with water in the aqueous medium becomes balanced at a certain concentration of the surfactants, which results in the formation of the micelle and regarding the concentration of the surfactants is termed as critical micelle concentration (*cmc*) [2-4]. These surfactant micelles can incorporate the drug molecules with lower aqueous solubility into the micelle core and consequently the higher solubility of the drugs. Due to this unique solubility and solubilizing properties of the surfactants, they are extensively used in pharmaceuticals as solubilizing, wetting as well as emulsifying agent [3,5]. In the textile industries, surfactants are used as dispersing, leveling, wetting as well as solubilizing agent [6,7]. Besides these, surfactants are important and essential ingredients in detergents and cosmetics. In the extraction/separation phenomenon of different metal ions and enzymes, surfactants show a significant character [8]. To gain insight the interaction of drugs or any other additives with the biological membrane, surfactant micelle can be considered as a typical bio-membrane [9]. The drug release rate in the aqueous vicinity of the human body is a function of surfactant content used in the formulation of drug [10]. Besides, surfactants are extensively utilized to synthesize nanoparticles for biomedical applications [11].

SDS is a very common surfactant that is used as food preservative, detergent, and a common ingredient in the case of DNA ex-

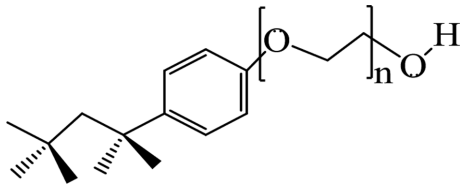
†To whom correspondence should be addressed.
E-mail: ahoque_ju@yahoo.com, mahmed4@ksu.edu.sa



Scheme 1. Molecular design of CFH.



Scheme 2. Molecular model of SDS.



Scheme 3. Molecular model of TX-100.

traction. SDS is useful in the detection and separation of protein molecules in the analytical biochemistry effectively. SDS, sodium dodecylbenzene sulfonate, and Triton X-100 mixture can significantly be employed in the synthesis and stabilization of nano-particles. TX-100 can be applied in the extraction of protein/DNA [12], metal plating, and soft composite preparation by dispersing carbon materials [8]. TX-100 is a very common component of the influenza vaccine. CFH is one of the most familiar antibiotic drugs that belong to fluoroquinolone groups. It is applied for the treatment of bacterial infection in different body parts, e.g., urinary tract, bone, and joints, respiratory tract. Again, it is an exceptional drug that has been prescribed to treat diarrhea, fever, anthrax, ear inflammation and intra-abdominal infection. Nonionic surfactants like TX-100 exhibit a decrease of solubility with cloudy formation when the solution temperature is increased above a certain level, and this temperature is known as the cloud point (CP) [13]. This is the characteristic value of each nonionic surfactant and is found to affect by the presence of additives.

Different types of additives present in the body or used in the formulation of a drug can affect drug+surfactant interaction, which can alter the drug release rate. Thus, to get better drug release and optimum activity of the drug, the drug interaction through surfactants in the occurrence of different additives is imperative from the applied perspective. Though literature reports a large number of publications on drug+surfactant interaction [11,14-18], the interaction of CFH with SDS/TX-100 is rare. Herein, our devised research was on the binding interaction of CFH (Scheme 1) with SDS (Scheme 2) and TX-100 (Scheme 3) in aqueous (at different pH), alcoholic medium as well as in zinc sulfate ($ZnSO_4 \cdot 7H_2O$) solution by means of the UV-Visible spectroscopic and cloud point measurement techniques. UV-visible measurement is a very simple, delicate, as well as fast method. This technique is frequently utilized to investigate the interactions amid the constituents of the pure and mixed system.

To have clear knowledge on the manner of interaction between drug and surfactants, a number of physico-chemical parameters such as binding constant (K_b), cloud point (CP), thermodynamic quantities of binding and clouding processes, thermodynamic parameters of transfer as well as enthalpy-entropy compensation parameters of CFH+SDS & CFH+TX-100 complexes have been evaluated in H_2O (at different pH), as well as alcoholic (methanol/propanediol)/$ZnSO_4 \cdot 7H_2O$ solution media. Even though the interaction between the drug and the surfactant is essential to advance actual drug release along with delivery and increase drug bioavailability; the activity of the surfactant can be expressively changed through the degree of several interactions (hydrophobic as well as hydrophilic) that happen both inside as well as exterior of the cell through numerous additives. Prior to a surfactant being established into a suitable drug carrier, a comprehensive investigation should be made to inspect the interaction of surfactant with the proposed drug.

EXPERIMENTAL

1. Materials

Analytical grade chemicals were utilized for this study. All the chemicals were utilized without any further purification. The source/provenance, purity, and grade of the chemicals used are outlined in Table 1. All the needed solutions were prepared employing distilled-deionized water having specific conductivity<2×10^{-6} S cm^{-1} within the temperature range of 293.15 to 308.15 K.

2. UV-visible spectroscopic technique

A computerized UV-Visible spectrophotometer (Shimadzu UV-1601PC) with a thermostatic cell holder was used to carry out the

Table 1. The source/provenance, purity, and grade of the chemicals used

Name of the chemicals	Source/Provenance	Purity	Grade
CFH	The ACME laboratories, Bangladesh	0.98	Analytical Grade
SDS	BDH, England	0.985	Analytical Grade
TX-100	Merck, Germany	0.99	Analytical Grade
Methanol	Active Fines Chemicals, Bangladesh	1.0	Analytical Grade
1,2-Propanediol	Rieedel-de-haen, Germany	0.995	Analytical Grade
NaOH	Merck, Germany	0.98	Analytical Grade
$ZnSO_4 \cdot 7H_2O$	Merck, India	0.99	Analytical Grade

study. Shimadzu-TCC-240A electrical temperature controller having the capability to regulate the temperature over the range of 7-60 °C was connected to the cell holder. The employed temperature controller works with the accuracy of ±0.5 °C. The spectrophotometer was controlled by a computer with UV-PC software. 1 cm^2 top quartz cells (3 mL) were used for the experimental purpose. Before each measurement, the baseline of spectrophotometer was calibrated against the corresponding solvent. Deionized H_2O with specific conductivity less than 2 $\mu S \cdot cm^{-1}$ up to 320.15 K was employed for solution formulation throughout the study. 5 mL of each solution (drug and surfactant) was added to 25 mL volumetric flask and then it was placed in a temperature-controlled electrical shaker (GFL 3031, USA) for shaking at 50 rpm and at the desired temperature [19]. After shaking for about 1 hour to attain an equilibrium, UV-spectrum was recorded [19]. The complete procedure was repeated at least for three times to check the reproducibility. To avoid the vaporization of alcoholic solvents, a cap was used for the volumetric flasks/cuvettes. The pH of the drug+surfactant systems was maintained at the desired value using HCl and NaOH.

3. Cloud Point Measurement Technique

To examine the clouding phenomenon of CFH+TX-100 solutions, first CFH+TX-100 solutions were prepared in the desired solvent (H_2O+$ZnSO_4 \cdot 7H_2O$ media having a particular concentration of salt) in such a way that both the CFH and TX-100 contained the desired concentration. The prepared solutions were stirred for about half-an-hour to reach a stable state. Both CFH and TX-100 are easily water-soluble and a clear solution was obtained within the concentration limit of the studied cases. The current study was carried out following the earlier reported procedures [13,20]. The CFH+TX-100 solutions (5 mL) were taken into Pyrex glass tubes which were formerly placed in a water bath. The temperature of the solutions was maintained using a manually prepared water bath and the arrival or vanishing of clouding (turbidity) was monitored visually with heating and cooling of the solutions, respectively. The corresponding temperatures of the arrival or vanishing of clouding were noted, and the mean of the temperatures was reflected as the cloud point (CP) [13,20]. To obtain the best result, the process was replicated at least three times and the reproducibility of the CP values was 0.2 K.

RESULTS AND DISCUSSION

1. Spectroscopic Study of the Binding between CFH and Surfactants

1-1. The Absorption Spectra of CFH/CFH+Surfactant Mixture and their Binding Phenomenon

To observe the ciprofloxacin-surfactant interaction, UV-Vis spectra were recorded at different conditions like temperature, pH, and in varying solvents. The absorption spectra of 4×10^{-5} CFH in the manifestation of numerous contents of SDS recorded at 298.15 K are shown in Fig. S1 (Supplementary materials). The absorbance values were found to increase with rising SDS concentration (10 to 50 mM) and λ_{max} changed from 275.6 nm to 280.0 nm. It was reported that the Quinolone drug, CFH, displays a maximum absorption at 275.60 nm [21]. This shift in λ_{max} and change in absorbance indicates that there is an interaction between CFH and SDS.

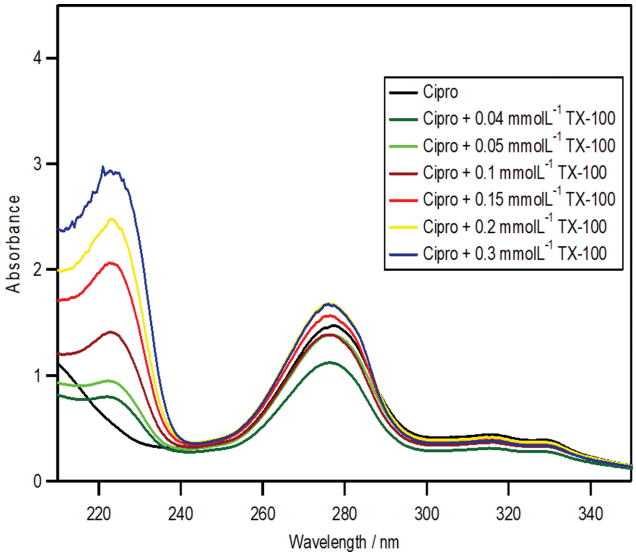


Fig. 1. Absorption spectra for pure CFH solution (4×10^{-5} mol L^{-1}) and CFH+TX-100 system having CFH concentration of 4.0×10^{-5} M at 293.15 K.

Also, the intensification in absorbance with growing surfactant concentration is viewed as being initiated by the drug molecules into the micelles as detected in other circumstances [22]. The absorption spectrum for the CFH+TX-100 mixture having 4×10^{-5} M CFH and variable TX-100 is depicted in Fig. 1. The absorbance of the CFH+TX-100 mixture undergoes an increase with developing amphiphile concentration. When the UV-spectra of CFH+TX-100 were carried out, a new shoulder at 223.4 nm was observed in each case that was absent in the spectra of pure CFH and pure TX-100. The development of new shoulder at 223.4 nm in the UV-spectra of CFH+TX-100 certainly indicates that strong interaction occurs between CFH and TX-100 as well as there is a drug-surfactant charge transfer (CT) complex formation [23]. Such an additional new band in the absorption was characterized as the CT band in different studies [24,25]. TX-100 was found to be performed as a donor molecule for CT complexation with some dyes and erythrosine [26,27]. Herein, there is a possibility of performing of CFH and TX-100 as acceptor and donor, respectively, to form the complex.

The UV-Vis spectra of 4.0×10^{-5} M CFH at different temperatures show a peak at 275.6 nm. Although there is no observable alteration in λ_{max} with developing temperature, the absorbance decreases with the rise of temperature. This peak has been recognized for the existence of the CFH monomer. In low concentration solution, there is a tendency of aggregation of ionic drugs, which leads to dimer formation and occasionally aggregates of greater-order are formed [28].

The absorbance was found to be higher at lower pH (less than 2), that is, in strongly acidic conditions. This can be correlated by the proposed different protonated forms of CFH [29]. When the pH is lower than 2, positively charged centers at multiple points of CFH are produced, which also facilitates the keto-enol tautomerism [29,30]. In the present case, the resonance effect between -OH group and P-π conjugation of the quinoline ring accelerates the

excitation of delocalized π electrons [29]. This facilitation under lower pH results in relatively higher absorbance values and at relatively lower energy too. In distilled water, the pH of the solution is slightly acidic (ranging from 5.3 to 5.5) and the observed small hypsochromic shift in this case may be due to the singly protonated species [29]. The λ_{max} also changes up to pH 7 but remains constant when in a basic pH range. This can be attributed to the formation of some new protonated species in the solution. At pH 7, the form of CFH exists as uncharged molecule. The decrease in absorbance is linked with different zwitterionic equilibrium forms existing at this stage. As soon as the pH goes to the basic region, there is an increase in the absorbance. This may be due to the formation of the stable carbonyl species and its hydrogen bonding to the aqueous medium, which is facilitated by the basic medium [31]. It was reported that in the micellar concentration range of surfactant (greater than *cmc*) organic dye molecules penetrate in the outer surface of the micelle [32]. Organic compounds containing sulphonic and carboxylic groups are incorporated in the stern layer of the micelle of ionic amphiphiles as sandwich alignment [32]. In a surfactant concentration of greater than *cmc* drug molecules might be solubilized in the stern layer of the surfactant micelle [33].

1-2. Evaluation of Binding Constant (K_b) of the Complexation of CFH with SDS and TX-100

The K_b values of the interaction of CFH with SDS and TX-100 were measured using Benesi-Hildebrand Eq. (1) [19,34,35].

$$[D]/A=1/K_b\varepsilon[C]+1/\varepsilon \quad (1)$$

where [D] and [C] reveal concentrations of drug and surfactant, respectively, whereas A and ε denote the absorbance and molar absorption coefficient, respectively, for drug+surfactant complexes. From the intercept ($1/\varepsilon$) and slope ($1/K_b\varepsilon$) of the Benesi-Hildebrand plots (Fig. 2), the binding constant (K_b) and molar absorption coefficient (ε) of drug+surfactant complexes were obtained. The values of binding constant (K_b) for CFH+SDS and CFH+TX-

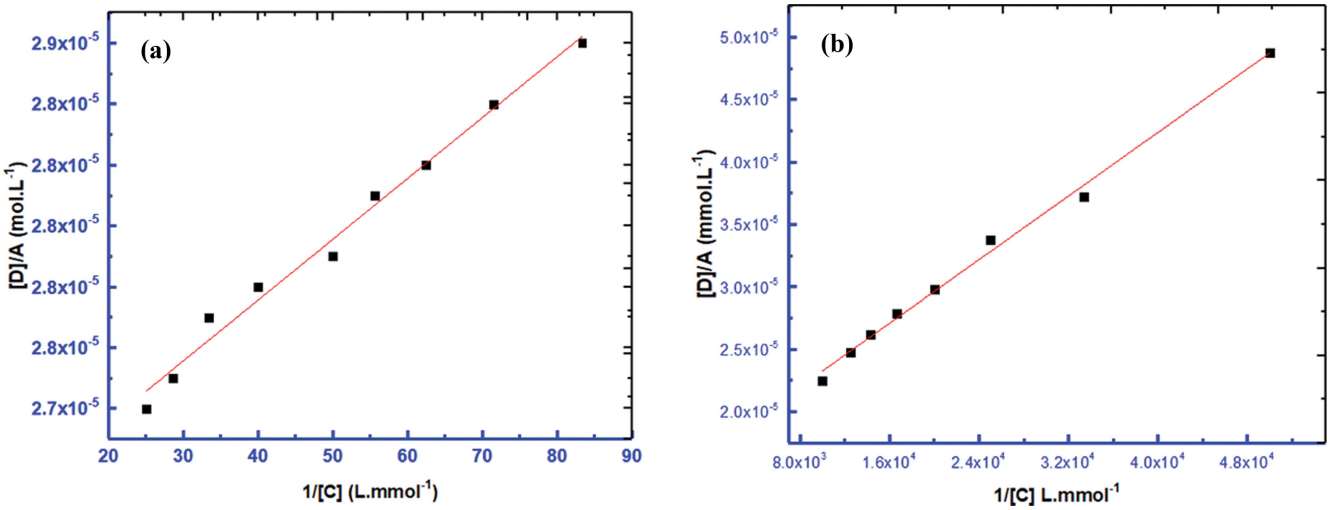


Fig. 2. The Benesi-Hildebrand plot for (a) CFH+SDS (b) CFH+TX-100 complex having CFH concentration of 4.0×10^{-5} M at 303.15 K in an aqueous medium.

Table 2. The values of binding constants of CFH with surfactants having 4.0×10^{-5} M CFH in different medium and temperatures[a]

System	Medium	$K_b\times10^{-3}$ ($Lmol^{-1}$)			
		293.15 K	298.15 K	303.15 K	308.15 K
CFH+SDS	Water (pH=6.5)	1.00	1.43	1.37	0.45
	10% Methanol	0.30	1.18	0.67	0.20
	20% Methanol	0.20	0.82	0.77	0.69
	30% Methanol	1.50	0.49	0.22	0.16
	10% Propanediol	0.43	0.77	0.62	0.37
	Water (acidic; pH=2.0)	1.00	0.16	0.22	0.55
	Water (Basic; pH=9.0)	0.40	0.43	0.36	0.23
CFH+TX-100	Water (pH=6.5)	15.00	91.28	46.09	26.55
	10% Methanol	150.0	199.2	181.8	64.18
	10% Propanediol	50.00	280.1	77.09	64.18
	Water (acidic; pH=2.0)	33.33	91.99	114.7	374.1
	Water (Basic; pH=9.0)	40.00	23.64	17.43	12.17

[a]Relative standard uncertainties (u_r) limits are $u_r(K_b)=\pm3\%$. All % are in v/v basis.

100 systems in various solvents media at different temperatures are presented in Table 2.

The estimated values of K_b for CFH+SDS complex were found to be higher in the aqueous medium than that of the alcoholic medium almost in all cases. By the structural rearrangement in CFH, a positive charge on N atom can be developed which attracts the negative charge of O atom of (SO_4^{2-}) of the monomeric SDS and facilitates the binding between SDS and CFH [16]. Again, binding is prohibited by the repulsion between the negative charge at the micelle-H_2O interface of a charged head of SDS micelles and oxygen (C=O) of quinolone group in CFH [16]. The development of N^+ ion is a function of the acidity of the medium. The acidity of the medium reduced in the presence of alcohol and the development of N^+ charge thus lowers electrostatic attraction between the N^+ of CFH and SO_4^{2-} ion of SDS is lower in an alcoholic medium. In the aqueous medium, the electrostatic attraction between the positively charged center of CFH (N^+) and SO_4^{2-} ion of SDS is dominant over the repulsive force between negative charge of SDS (SO_4^{2-}) and oxygen of quinolone group in CFH. So the binding constant values of CFH with SDS are lower in alcoholic medium as compared with aqueous system. The obtained values of K_b of CFH with SDS were found to be less in the acidic medium than that of H_2O. The result may be due to the neutralization of SO_4^{2-} ion of SDS by H^+ ion and N^+ charge of CFH by Cl^- ion. In the basic condition, a negative charge on CFH is developed which repels the SO_4^{2-} ion of SDS, which reduces the binding between SDS and CFH. The K_b values of CFH+SDS complexes initially increase, reach a maximum point and then again reduce with upsurge of temperature in almost all media except in 30% (v/v) methanol (the K_b values drecreased gradually with temperature) and water medium having pH=2.0 (the K_b values drecreased, attained a minimum value and then again increased with temperature rise). The observed K_b values of CFH+TX-100 complexes were found to be less in basic medium (except at 293.15 K) while higher in an acidic medium as compared to an aqueous medium. TX-100 is a non-ionic surfactant; thus the hydrophobic interaction amongst the TX-100 and CFH is facilitated in presence of organic additive like alcohol. So the values of K_b for CFH+TX-100 complexes are higher in alcoholic medium (Table 2). For the CFH+TX-100 complexes the K_b values primarily upsurge, touch a maximum point and then yet again reduce with rise of temperature in almost all media except in water (basic; pH=9.0) (where the K_b values drecreased gradually with temperature).

The hydration of polar head group of surfactants decreases with the increase of temperature, which makes polar group of surfactants more available for CFH through electrostatic interactions and thus the K_b value increases. But the molecular movement of the drug/surfactants increases with the increase of temperature, which disfavors the binding between drug and surfactants which consequences the lower values of K_b at higher temperature of CFH with SDS (except 30% methanol and acidic media) as well as TX-100 (except in basic medium). Hydrophilic hydration of the polar part of the surfactants reduces with the increase of temperature, which makes polar parts of the surfactants more available to the N^+ ions of CFH at multiprotonated state in acidic medium, and thus K_b of CFH with SDS as well as TX-100 increases with increasing temperature.

1-3. Thermodynamics of the Binding of Drug with Surfactants

Various thermodynamic parameters coupled with the binding of CFH with SDS/TX-100 were calculated from the subsequent standard thermodynamic equations [15,36-41]:

$$\Delta G_b^o = -RT\ln K_b \quad (2)$$

$$\Delta H_b^o = RT^2(\partial \ln K_b)/\partial T \quad (3)$$

$$\Delta S_b^o = (\Delta H_b^o - \Delta G_b^o)/T \quad (4)$$

where, R and T bear their usual meanings. In Eq. (3), the value $(\partial \ln K_b)/\partial T$ was determined from the slope of $\ln K_b$ vs. T plot. The values of $\ln K_b$ vary almost nonlinearly with temperature for CFH+SDS and CFH+TX-100 systems in all the media studied except CFH+TX-100 system in acidic (pH=2.0) and basic (pH=9.0) media where linear behavior is observed. For nonlinear plots, slopes were determined corresponding to each temperature. For the linear plot of $\ln K_b$ vs. T, one slope was used to estimate ΔH_b^o [42]. A typical graph of $\ln K_b$ vs. T for CFH+TX-100 system in acidic (pH=2.0)

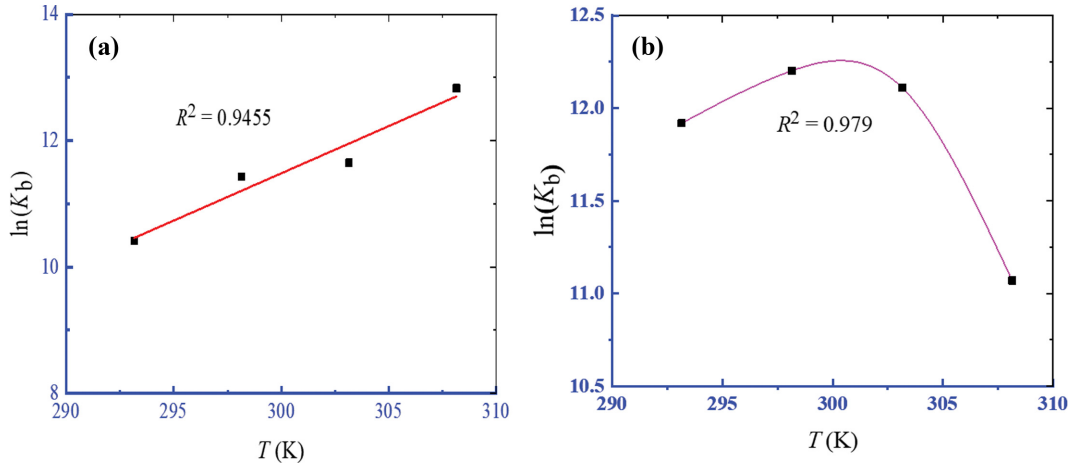


Fig. 3. The plot of $\ln K_b$ vs T for CFH+TX-100 system (a) in acidic water (pH=2.0) and (b) in 10% (v/v) methanol solution where in both cases CFH concentration is 4.0×10^{-5} M.

Table 3. The values of different thermodynamic parameters associated with drug+surfactant system having CFH concentration of 4.0×10^{-5} M[a]

System	Medium	T	ΔG_b^o	ΔH_b^o	ΔS_b^o
		K	kJ·mol^{-1}	kJ·mol^{-1}	J mol^{-1}·K^{-1}
CFH+SDS	Water (pH=6.5)	293.15	−16.84	51.11	231.8
		298.15	−18.01	52.87	237.7
		303.15	−18.20	−170.1	−501.2
		308.15	−15.65	−175.8	−519.7
	10% Methanol	293.15	−13.90	195.7	715.0
		298.15	−17.53	202.4	737.7
		303.15	−16.40	−184.7	−555.3
		308.15	−13.57	−190.9	−575.4
	20% Methanol	293.15	−12.91	201.6	731.8
		298.15	−16.63	208.6	755.3
		303.15	−16.75	−16.76	−0.0387
		308.15	−16.75	−17.32	−1.863
	30% Methanol	293.15	−17.82	−159.9	−484.6
		298.15	−15.35	−165.4	−503.2
		303.15	−13.59	−48.66	−115.7
		308.15	−13.00	−50.28	−121.0
	10% propanediol	293.15	−14.77	83.58	335.5
		298.15	−16.48	86.46	345.2
		303.15	−16.21	−78.88	−206.8
		308.15	−15.15	−81.51	−215.3
	pH=2.0	293.15	−16.84	−261.9	−835.9
		298.15	−12.58	−270.9	−866.3
		303.15	−13.59	140.0	506.7
		308.15	−16.17	144.7	522.0
	pH=9.0	293.15	−14.60	10.33	85.07
		298.15	−15.03	10.69	86.27
		303.15	−14.84	−68.46	−176.9
		308.15	−13.93	−70.74	−184.4
CFH+TX-100	Water (pH=6.5)	293.15	−23.44	258.1	960.2
		298.15	−28.31	266.9	990.3
		303.15	−27.06	−84.29	−188.8
		308.15	−26.10	−87.09	−197.9
	10% Methanol	293.15	−29.05	40.50	237.2
		298.15	−30.25	41.89	242.0
		303.15	−30.52	−159.1	−424.1
		308.15	−28.36	−164.4	−441.4
	10% propanediol	293.15	−26.37	246.2	929.9
		298.15	−31.09	254.7	958.5
		303.15	−28.36	−28.01	1.167
		308.15	−28.36	−28.94	−1.881
	pH=2.0	293.15	−25.38	106.8	451.0
		298.15	−28.33	110.5	465.6
		303.15	−29.36	114.2	473.7
		308.15	−32.88	118.0	489.7
	pH=9.0	293.15	−25.83	−55.37	−100.8
		298.15	−24.96	−57.28	−108.4
		303.15	−24.61	−59.21	−114.1
		308.15	−24.10	−61.18	−120.3

[a]Relative standard uncertainties (u_r) limits are $u_r(\Delta G_b^o)=\pm3\%$, $u_r(\Delta H_b^o)=\pm4\%$ and $u_r(\Delta S_b^o)=\pm5\%$. All % are in v/v basis

medium and 10% (v/v) methanol solution is demonstrated in Fig. 3.

The values of ΔG_b^o and ΔH_b^o obtained from Eqs. (2) and (3) were subsequently employed in Equation (4) to get the values of ΔS_b^o. The calculated values of ΔG_b^o, ΔH_b^o and ΔS_b^o are provided in Table 3. The ΔG_b^o values are found to be negative for binding of CFH with both surfactants (SDS and TX-100) in all cases investigated, which signifies that binding of CFH to SDS and TX-100 is thermodynamically spontaneous. The calculated values of ΔG_b^o for CFH+SDS system were more negative in an aqueous medium, which implies that binding of CFH with SDS in aqueous medium is more spontaneous than the other solvents investigated and this result is well in agreement with the values of K_b (higher in aqueous medium) (Table 2).

The calculated value of ΔG_b^o for CFH+TX-100 system was more negative in alcoholic/diol media compared to aqueous medium having pH values of 6.5 and 9.0, which reveals that the binding of CFH with TX-100 is extra spontaneous in alcoholic/diol media, which is well supported by the values of K_b (higher in alcoholic medium) (Table 2). In aqueous medium having pH=2.0, the ΔG_b^o value for CFH+TX-100 system was obtained to be much greater at 308.15 K. The estimated values of ΔH_b^o for the CFH+SDS system in H_2O and aq. methanol/diol media were positive at lower temperature (293.15 and 298.15 K) and negative at higher temperature (303.15 and 308.15 K) except in 30% (v/v) methanol solution (ΔH_b^o values are achieved negative at all temperatures) and acidic condition (negative and positive at lower and higher temperature, respectively). The results signify that binding of CFH and SDS is endothermic at lesser temperature and exothermic at upper temperature in solvents utilized, except in 30% methanol (exothermic at all temperatures) and acidic condition (exothermic at lower temperature and endothermic at upper temperature). The estimated negative values of ΔH_b^o for CFH+SDS system (except in 30% methanol and acidic condition) increase with the boost of temperature, which indicates that binding is more exothermic at higher temperature. The estimated values of ΔS_b^o for CFH+SDS system exhibit the same trend like ΔH_b^o in all cases (Table 3). The values of ΔH_b^o and ΔS_b^o in aqueous medium signify that the binding of CFH with SDS is entropy dominated at lower temperature and enthalpy dominated at higher temperature in H_2O, aq. methanol (10 & 20% v/v), aq. 10% (v/v) propanediol and in basic medium (pH=8.5); enthalpy dominated at all temperature in 30% methanol medium while completely entropy and enthalpy dominated at lower and higher temperatures, respectively in acidic medium. The values of ΔH_b^o and ΔS_b^o for the CFH+TX-100 system in H_2O and aqueous alcoholic/diol were positive and negative at lower and upper temperature, respectively, which reveals that binding of CFH and TX-100 is endothermic and exothermic at lower and upper temperature, respectively. The values of ΔH_b^o and ΔS_b^o for CFH+TX-100 system in the acidic medium (pH=2.0) are positive at all temperatures and undego an upsurge with elevation of temperature, which means that CFH+TX-100 binding is endothermic as well as entropy dominated. In the basic medium (pH=9.0), the values of ΔH_b^o and ΔS_b^o for CFH+TX-100 system are negative at each employed temperature and the negative values decrease through increase of temperature, which indicates that CFH+TX-100 binding is exothermic as well as enthalpy organized. The negative values of ΔH_b^o and ΔS_b^o reveal the existence of H-bonding, dipole-dipole, or ion-dipole forces between drug (CFH) and surfactants (SDS/TX-100) [43,44]. The negative values of ΔH_b^o imply that hydrophilic hydration of the surfactants dominates over the ruin of 3D water structure around the hydrophobic portion of the surfactants [45,46], while positive values connote the higher disorder of H_2O structure around the tails of the surfactants [47,48]. The negative values of ΔH_b^o also imply the presence of London dispersion force between CFH and surfactant (SDS/TX-100), which is the prominent force of interaction among the CFH and surfactants (SDS/TX-100) [49].

1-4. Thermodynamic Parameters of Transfer for the Binding of Drug with Surfactants

For better clarification of the drug-surfactant interaction, the values of different thermodynamic parameters of transfer for the transfer of the system from water (pH=6.5) to other solvents and water (pH: 2 and 9) were also assessed using Eqs. (5), (6) and (7) [48,50,51].

$$\Delta G_{b,tr}^o = \Delta G_b^o(\text{additive sol.}) - \Delta G_b^o(\text{aq.}) \quad (5)$$

$$\Delta H_{b,tr}^o = \Delta H_b^o(\text{additive sol.}) - \Delta H_b^o(\text{aq.}) \quad (6)$$

$$\Delta S_{b,tr}^o = \Delta S_b^o(\text{additive sol.}) - \Delta S_b^o(\text{aq.}) \quad (7)$$

Estimated values of free energy of transfer ($\Delta G_{b,tr}^o$), enthalpy of transfer ($\Delta H_{b,tr}^o$) and entropy of transfer ($\Delta S_{b,tr}^o$) are in Table 4. The $\Delta G_{b,tr}^o$ values for the CFH+SDS system were found to be positive almost in all cases (except in very few cases), which means that spontaneity of binding is reduced in the presence of investigated additives/with the variation of pH; thus, the binding constants for CFH+SDS system are lower in the presence of investigated additives. On the contrary, the values of $\Delta G_{b,tr}^o$ for CFH+TX-100 system in the alcoholic, diol and acidic medium were found to be negative (Table 4), which reveals that binding of CFH with TX-100 is facilitated in those media and hence more spontaneous binding of CFH with TX-100 occurs; consequently K_b values increased in those media as compared to an aqueous solution. The $\Delta G_{b,tr}^o$ values of CFH+TX-100 system in basic medium (pH=9.0) are positive except at 293.15 K, which reveals less spontaneity of CFH+TX-100 binding, which has been supported by the lower K_b values. The values of $\Delta H_{b,tr}^o$ and $\Delta S_{b,tr}^o$ for the CFH+SDS system were negative at lower temperature and positive at upper studied temperature (except 10 and 20 % (v/v) methanol solution as well as 10% (v/v) diol solution). In 10 % (v/v) methanol solution, the values are positive at lower employed temperature and negative at higher studied temperature, while in 20% (v/v) methanol as well as 10% (v/v) diol solutions the values are positive at all temperatures. The values of $\Delta H_{b,tr}^o$ and $\Delta S_{b,tr}^o$ for the CFH+TX-100 system were negative in 10% (v/v) methanol solution, whereas in other solvents both the values were negative and positive at lower and upper temperature, respectively.

1-5. Enthalpy-entropy Compensation for the Binding of Drug with Surfactants

The ΔH_b^o and ΔS_b^o values monotonically changed with temperature and both have the opposite effect on the ΔG_b^o. So the ΔH_b^o and ΔS_b^o values compensate each other to contribute the resultant effect on the ΔG_b^o. A good linear relation between ΔH_b^o and ΔS_b^o is stated as enthalpy-entropy compensation, and in the current study an

Table 4. Various thermodynamic parameter values of transfer associated with drug+surfactant system having CFH concentration of 4.0×10^{-5} M[a]

System	Medium	T	$\Delta G^{o}_{b,tr}$	$\Delta H^{o}_{b,tr}$	$\Delta S^{o}_{b,tr}$
		K	kJ·mol^{-1}	kJ·mol^{-1}	J mol^{-1}·K^{-1}
CFH+SDS	10% Methanol	293.15	2.934	144.6	483.2
		298.15	0.476	149.56	500.0
		303.15	1.803	−14.62	−54.16
		308.15	2.078	−15.10	−55.75
	20% Methanol	293.15	3.923	150.5	500.1
		298.15	1.379	155.7	517.6
		303.15	1.452	153.4	501.1
		308.15	−1.095	158.5	517.8
	30% Methanol	293.15	−0.988	−211.0	−716.3
		298.15	2.655	−218.2	−740.9
		303.15	4.610	121.5	385.5
		308.15	2.649	125.5	398.7
	10% propanediol	293.15	2.063	32.47	103.7
		298.15	1.534	33.59	107.5
		303.15	1.998	91.24	294.4
		308.15	0.501	94.28	304.3
	pH=2.0	293.15	0.000	−313.0	−1,068
		298.15	5.429	−323.7	−1,104
		303.15	4.610	310.1	1,008
		308.15	−0.514	320.5	1,042
	pH=9.0	293.15	2.233	−40.78	−146.7
		298.15	2.979	−42.18	−151.5
		303.15	3.368	101.66	324.2
		308.15	1.720	105.0	335.3
CFH+TX-100	10% Methanol	293.15	−5.612	−217.6	−723.0
		298.15	−1.934	−225.0	−748.3
		303.15	−3.458	−74.81	−235.4
		308.15	−2.261	−77.30	−243.5
	10% propanediol	293.15	−2.934	−11.83	−30.3
		298.15	−2.779	−12.24	−31.7
		303.15	−1.296	56.28	189.9
		308.15	−2.261	58.15	196.0
	pH=2.0	293.15	−1.946	−151.2	−509.3
		298.15	−0.019	−156.4	−524.6
		303.15	−2.298	198.5	662.4
		308.15	−6.778	205.1	687.6
	pH=9.0	293.15	−2.391	−313.4	−1,061
		298.15	3.349	−324.2	−1,099
		303.15	2.451	25.07	74.62
		308.15	1.998	25.91	77.58

[a]Relative standard uncertainties (u_r) limits are $u_r(\Delta G^{o}_{b,tr})=\pm3\%$, $u_r(\Delta H^{o}_{b,tr})=\pm4\%$ and $u_r(\Delta S^{o}_{b,tr})=\pm5\%$. All % are in v/v basis.

excellent linear relationship was observed between ΔH^{o}_{b} and ΔS^{o}_{b} for both CFH+SDS and CFH+TX-100 systems; thus entropy-enthalpy compensation parameters were assessed solving Eq. (8) [52-56].

$$\Delta H^{o}_{b}=\Delta H^{o,*}_{b}+T_c\Delta S^{o}_{b} \quad (8)$$

In Eq. (8), the intercept of ΔH^{o}_{b} vs. ΔS^{o}_{b} plot is intrinsic enthalpy ($\Delta H^{o,*}_{b}$) while their slope denotes compensation temperature (T_c). A representative plot of ΔH^{o}_{b} against ΔS^{o}_{b} is given in Fig. 4. The values of $\Delta H^{o,*}_{b}$ and T_c are visualized in Table 5. It is well reported that micellization of surfactants consists of a two part process: desolvation part, i.e., the destruction of water structure surrounding the hydrophobic tail/regions of surfactants, and chemical part of micelle formation, i.e., the aggregation of hydrophobic parts to form the core of micelles. Chen et al. [53] proposed that T_c decribes the solute-solute and solute-solvent interactions, that is, it is the measure

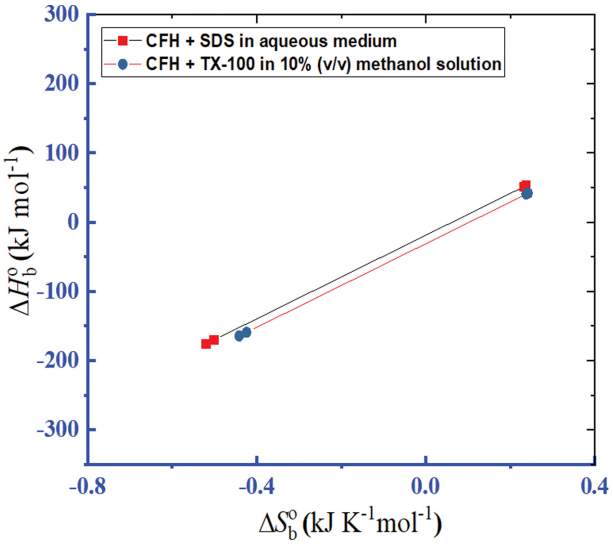


Fig. 4. Enthalpy-entropy compensation for CFH+surfactant mixture having CFH concentration of 4.0×10^{-5} M.

of the desolvation part pof the process. They also proposed that that intercept $\Delta H_b^{o,*}$ refers to the solute-solute interaction which can be accepted as the index of the effectiveness of the chemical part process. It is also reported that T_c is referred to as the characteristic of hydrophobic interaction between solvent and solute species, while the $\Delta H_b^{o,*}$ is the degree of solute-solute interaction [54-56].

Jolicoeur and Philip [54] reported that T_c is characteristic of hydrophobic interactions of the clustering of solute specices. They also proposed that T_c values can also be used to characterize the hydrophobic interactions originating from the pairwise interaction between the hydrophobic/inert solutes present in the solutions [54]. The values of $\Delta H_b^{o,*}$ were found negative in each case, which signifies that drug+surfactant complex formation is facilitated in all cases (Table 5). The negative $\Delta H_b^{o,*}$ values signify the stability of the drug+surfactant complex formed. When $\Delta S_b^o=0$, then the $\Delta H_b^{o,*}$ becomes equal to the ΔH_b^o. The values of $\Delta H_b^{o,*}$ are higher for CFH+TX-100 complex than that of CFH+SDS complex, which reveals the higher stability of CFH+TX-100 complex formed (Table 5). In the cases of methanol/propanediol solutions and acidic H_2O/basic H_2O media, the $\Delta H_b^{o,*}$ values are nearer to the ΔG_b^o values, which tells that the CFH+TX-100 binding process is governed by the additive-water interactions, which leads to the change of water structure in the occurrence of additives. Chauhan et al. [55] obtained more closer values of $\Delta H_b^{o,*}$ and ΔG_b^o for the micellization of SDS in aqueous sugar solution, and they suggested that the SDS micellization might be governed by the existence of interactions between sugar and water molecules. The estimated T_c values for CFH+TX-100 and CFH+SDS systems lie in the range of 295.3-301.9 K. The T_c values in the range of 270-310 K give significant information of the involvement of water in protein solution [49] and our results are in this range in all cases.

2. Clouding Phenomenon of CFH+TX-100 Mixture

2-1. CP Values of CFH+TX-100 Mixture in $H_2O+ZnSO_4{\cdot}7H_2O$ Media

Clouding phenomenon is considered one of the characteristic properties of non-ionic surfactants. From the CP measurement, it is possible to determine the stability of the drug solution and that is why we have determined CP in this study. A phase separation of non-ionic surfactants solution occurs at CP [57]. At lower temperature, nonionic surfactants form hydrogen bonds with water molecules and they dissolve in water, but at higher temperature hydrogen bonds start to break, the solubility of surfactant decreases, and there is the appearance of two phases [1]. Formation of two phases indicates the reduction of actual solution properties. That is why we need to determine the temperature where phase separation occurs, because this information helps to protect products. In our earlier study, a decrease of CP values of CFH+TX-100 consisting 10 mmol kg^{-1} TX-100 in water was observed through the upsurge of CFH concentrations, while the CP values of CFH+TX-100 in water having 1 and 5 mmol kg^{-1} CFH were 333.55 and 334.33 K, respectively [58]. In the current study, we studied the effect of numer-

Table 5. The values of entropy-enthalpy compensation parameters associated with drug+surfactant system having CFH concentration of 4.0×10^{-5} M[a]

System	Medium	$\Delta H_b^{o,*}$	T_c	R^2
		kJ·mol^{-1}	K	
CFH+SDS	Water (pH=6.5)	−18.88	301.9	1
	10% Methanol	−18.49	299.5	1
	20% Methanol	−16.76	298.4	1
	30% Methanol	−13.82	301.3	1
	10% Propanediol	−16.96	299.6	1
	Water (acidic; pH=2.0)	−11.61	299.3	1
	Water (Basic; pH=9.0)	−15.26	300.9	1
CFH+TX-100	Water (pH=6.5)	−28.08	298.0	1
	10% Methanol	−31.12	301.8	1
	10% Propanediol	−28.37	295.3	1
	Water (acidic; pH=2.0)	−26.93	296.4	0.9861
	Water (Basic; pH=9.0)	−25.05	299.5	0.9957

[a]Relative standard uncertainties (u_r) limits are $u_r(\Delta H_b^{o,*})=\pm4\%$ and $u_r(T_c)\pm0.2$ K. All % are in v/v basis.

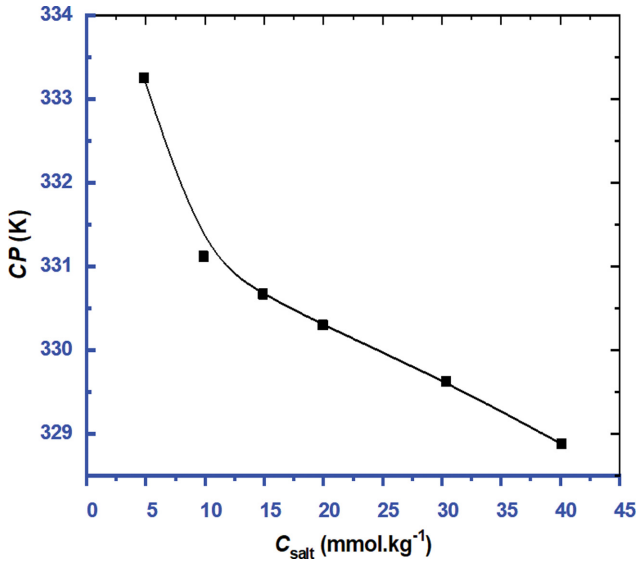


Fig. 5. The change in CP values of TX-100+CFH mixture through the concentration variation of $ZnSO_4 \cdot 7H_2O$ solution.

ous concentrations (4.82 to 40.12 mmol kg^{-1}) of $ZnSO_4 \cdot 7H_2O$ on the value of CP of CFH+TX-100 mixture. We found a CP value of 333.75 K for CFH+TX-100 in water having 3 mmol kg^{-1} CFH and 16.46 mmol kg^{-1} TX-100, which indicates a good agreement with our previous study [58]. As all the solutions were freshly and individually prepared, the concentrations of TX-100 and CFH were slightly varied from the desired fixed concentration (variation is almost negligible). The experimentally determined CP values of CFH+TX-100 mixture in aqueous $ZnSO_4 \cdot 7H_2O$ media are compiled in Fig. 5. The CP values for the TX-100+CFH mixed system decrease with the increasing concentration of salt. This type of result was also found by the previous researcher [59]. Due to the addition of salt, the salting-out effect of surfactant molecules occurs. The addition of salt may cause the surfactant molecules to come closer to each other by the release of water surrounding the amphiphile molecules, and hence there is a decrease in CP values [60]. The electrostatic attraction between salt and water is higher as compared to the water and polar head group of surfactant molecules. That is why electrolyte ($ZnSO_4 \cdot 7H_2O$) reduces the CP values.

2-2. Thermodynamics of Clouding for CFH+TX-100 Mixed System

Standard free energy change (ΔG_c^o), enthalpy change (ΔH_c^o) and entropy change (ΔS_c^o) of clouding phenomenon of CFH+TX-100 mixed system have been estimated by using the equations given below [61-63]:

$$\Delta G_c^o = -RT\ln X_s \quad (9)$$

$$\Delta H_c^o = RT^2 (\partial \ln X_s)/\partial T \quad (10)$$

$$\Delta S_c^o = (\Delta H_c^o - \Delta G_c^o)/T \quad (11)$$

Here, X_s is considered as the mole fraction concentration of the used additives (CFH/salt). To determine the ΔH_c^o, plots of $\ln X_s$ versus temperature were drawn and slopes at different T (CP) were taken as the values of $(\partial \ln X_s)/\partial T$. Such a schematic plot is shown in Fig. S2 (Supplementary materials).

The observed outcomes for the thermodynamic parameters of CFH+TX-100 mixture in aqueous salt solution are provided in Table 6. The detected ΔG_c^o values are positive for CFH+TX-100 mixture in the electrolyte solution, which indicates that the phase separation phenomenon is nonspontaneous. The positive ΔG_c^o values were decreased with the increasing concentration of salt, which reveals that the nonspontaneity of the clouding process of CFH+TX-100 mixture tends to decline with enhancing the content of electrolyte.

In existence of salt, the ΔH_c^o values of CFH+TX-100 mixture was negative for all concentrations of salt, and the magnitude of the ΔH_c^o values increased primarily through the enhanced concentration of salt and decreased after reaching a certain value. Thus, the clouding phenomenon observed for CFH+TX-100 mixture in zinc sulfate solution is exothermic. The ΔS_c^o values of the employed drug and surfactant mixed system are negative. The values of ΔH_c^o and ΔS_c^o of employed mixed system in $ZnSO_4 \cdot 7H_2O$ solution indicate that the clouding of the TX-100+CFH mixture is totally controlled by enthalpy change. Thus the ΔH_c^o and ΔS_c^o values of the mixed studied system suggest the presence of only the exothermic interactions, for example, H-bonding and dipole-dipole interaction between CFH and TX-100 in the salt medium.

The linear relation between enthalpy and entropy is referred to as enthalpy-entropy compensation, which obtained R^2 value of almost 1.00 for CFH+TX-100 mixed system in presence of $ZnSO_4 \cdot 7H_2O$. Using Eq. (8) in case of clouding, values of compensation temperature (T_c) and intrinsic enthalpy gain (ΔH_c^{0*}) were evaluated from the slope and intercept of ΔH_c^0 versus ΔS_c^0 plot (Fig. S3 (Supplementary materials)) [64,65]. T_c characterizes the solute-solute interactions and ΔH_c^{0*} clarifies the solute-solvent interactions. The

Table 6. CP values and their thermodynamic parameters of CFH+TX-100 mixture in $ZnSO_4 \cdot 7H_2O$ solution[a]

$C_{TX\ 100}$	C_{CFH}	C_{ZnSO_4}	CP	ΔG_c^o	ΔH_c^o	ΔS_c^o
mmol kg^{-1}	mmol kg^{-1}	mmol kg^{-1}	K	kJ mol^{-1}	kJ mol^{-1}	J mol^{-1} K^{-1}
15.65	3.10	4.82	333.25	25.91	−375.0	−1,203
16.54	3.14	9.88	331.12	23.77	−370.2	−1,190
16.49	2.91	14.90	330.67	22.61	−780.8	−2,430
16.30	3.10	19.95	330.30	21.78	−613.6	−1,924
16.53	2.92	30.34	329.63	20.59	−442.2	−1,404
16.22	3.02	40.12	328.88	19.78	−440.2	−1,399

[a]Relative standard uncertainties (u_r) limits are $u_r(\Delta G_c^o)=\pm 3\%$, $u_r(\Delta H_c^o)=\pm 4\%$ and $u_r(\Delta S_c^o)=\pm 5\%$.

T_c and ΔH_c^{0*} values of the TX-100+CFH mixed system in the salt solvent were found to be 330.84 K and 22.848 kJ mol^{-1}, respectively. This type of result was also found by previous researchers [52]. The T_c values obtained from the clouding study reveal good resemblance with the behavior of protein solutions in water [49].

CONCLUSION

The interaction of CFH drug with two surfactants (SDS and TX-100) has been studied through UV-Visible spectroscopy and cloud point measurement techniques in different solvent media and at variable temperatures. The obtained subsequent results are:

▶ The binding of CFH with SDS and TX-100 was reflected from the variation of absorbance and λ_{max} values in the case of spectroscopic study.

▶ The K_b values of CFH+SDS and CFH+TX-100 complexes are dependent on the composition and nature of media as well as the variation of temperature.

▶ The K_b values first increase, reach a maximum value and then decrease with the temperature in most of the cases.

▶ The ΔG_b^o values reveal that the binding phenomenon was spontaneous in each case.

▶ From the negative values of ΔH_b^o and ΔS_b^o, the existence of H-bonding, dipole-dipole or ion-dipole forces between drug (CFH) and surfactant (SDS/TX-100) are suggested.

▶ Addition of zinc sulfate reduces the CP values of CFH+TX-100 mixture which is further enhanced with rising content of electrolyte. The thermodynamic parameters revealed that the clouding of CFH+TX-100 mixture is a nonspontaneous, exothermic, and enthalpy driven phenomenon.

▶ Excellent linear relationship between enthalpy and entropy changes of binding and clouding phenomena was observed in each case.

▶ The negative $\Delta H_b^{o,*}$ values signify the stability of drug+surfactant complexes.

▶ The study involving CFH and SDS/TX-100 can be extended using molecular dynamics simulations to locate the interaction sites. In addition, the morphology of CFH+SDS/TX-100 might be studied applying TEM/SEM tools.

DECLARATION OF COMPETING INTEREST

The authors have declared that no competing interests exist.

ACKNOWLEDGEMENT

The authors extend their appreciation to the Deanship of Scientific Research at King Saud University for funding this work through research group no. RG-1441-461.

LIST OF ABBREVIATIONS

CFH	: ciprofloxacin hydrochloride
SDS	: sodium dodecyl sulfate
TX-100	: Triton X-100
$ZnSO_4 \cdot 7H_2O$	: zinc sulfate
MFP	: mass fractional purity
K_b	: binding constant
cmc	: critical micelle concentration
ΔG_b^o	: Gibbs free energy of binding
ΔH_b^o	: enthalpy of binding
ΔS_b^o	: entropy of binding
$\Delta G_{b,tr}^o$	: free energy of transfer
$\Delta H_{b,tr}^o$	: enthalpy of transfer
$\Delta S_{b,tr}^o$	: entropy of transfer
$\Delta H_b^{o,*}$	: intrinsic enthalpy
T_c	: compensation temperature
CP	: cloud point
ΔG_c^0	: Gibbs free energy of clouding
ΔH_c^0	: enthalpy of clouding
ΔS_c^0	: entropy of clouding

SUPPORTING INFORMATION

Additional information as noted in the text. This information is available via the Internet at http://www.springer.com/chemistry/journal/11814.

REFERENCES

1. M. J. Rosen, *Surfactants and interfacial phenomena*, 3rd Ed., John Wiley & Sons, New York (2004).
2. M. A. Hoque, S. Mahbub, M. A. Rub, S. Rana and M. A. Khan, *Korean J. Chem. Eng.*, **35**, 2269 (2018).
3. J.-C. Kim, *Korean J. Chem. Eng.*, **26**, 1821 (2009).
4. D. Kumar and M. A. Rub, *J. Phys. Org. Chem.*, **32**, e3946 (2019).
5. S. Mahbub, M. Rahman, S. Rana, M. A. Rub, M. A. Hoque, M. A. Khan and A. M. Asiri, *J. Surfactants Deterg.*, **22**, 137 (2019).
6. Ç. Kartal and H. Akbaş, *J. Mol. Liq.*, **65**, 191 (2005).
7. E. D. Goddard and K. P. Ananthapadamanabham (Eds.), *Interactions of surfactants with polymer and proteins*, CRC Press, Boca Raton (1993).
8. M. A. Rahim, S. Mahbub, M. K. Islam, S. M. A. Ahsan, S. Rana, M. A. Rub, A. Khan and M. A. Hoque, *J. Surfactants Deterg.*, **23**, 457 (2019).
9. J. N. Israelachvili, *Intermolecular and surface forces*, 2nd Ed., John Wiley & Sons, New York (1995).
10. V. Bhardwaj, T. Bhardwaj, K. Sharma, A. Gupta, S. Chauhan, S. S. Cameotra, S. Sharma, R. Gupta and P. Sharma, *RSC Adv.*, **4**, 24935 (2014).
11. H. Huang, M. Liu, R. Jiang, J. Chen, L. Mao, Y. Wen, J. Tian, N. Zhou, X. Zhang and Y. Wei, *J. Colloid Interface Sci.*, **513**, 198 (2018).
12. D. Koley and A. J. Bard, *Proc. Natl. Acad. Sci. U. S. A.*, **107**, 16783 (2010).
13. S. Mahbub, *J. Mol. Liq.*, **307**, 112912 (2020).
14. S. Sharma, K. Kumar, S. Chauhan and M. S. Chauhan, *J. Mol. Liq.*, **297**, 111782 (2020).
15. M. Enache and A. M. Toader, *J. Surfactants Deterg.*, **21**, 31 (2018).
16. T. S. Banipal, R. Kaur and P. K. Banipal, *J. Mol. Liq.*, **255**, 113 (2018).
17. A. Techen, C. Hille, C. Dosche and M. U. Kumke, *J. Colloid Interface Sci.*, **377**, 251 (2012).
18. A. M. Khan and S. S. Shah, *J. Dispers. Sci. Technol.*, **30**, 997 (2009).

19. S. Mahbub, I. Shahriar, M. Iqfath, M. A. Hoque, M. A. Halim, M. A. Khan, M. A. Rub and A. M. Asiri, *J. Environ. Chem. Eng.*, **7**, 103364 (2019).
20. M. A. Rahim, S. Mahbub, S. M. A. Ahsan, M. Alam, M. Saha, I. Shahriar, S. Rana, M. A. Halim, M. A. Hoque and D. Kumar, *J. Mol. Liq.*, **322**, 114683 (2021).
21. E. C. L. Cazedey and H. R. N. Salgado, *Adv. Anal. Chem.*, **2**, 74 (2012).
22. S. G. Bertolotti, N. A. García and H. E. Gsponer, *J. Colloid Interface Sci.*, **129**, 406 (1989).
23. Z. A. Khan and A. S. Al-Bogami, *Asian J. Chem.*, **25**, 10499 (2013).
24. N. Alizadeh and Z. A. Tavani, *Iran. J. Chem. Chem. Eng.*, **37**, 47 (2018).
25. N. Alizadeh and S. Dehganikhah, *J. Solution Chem.*, **45**, 42 (2016).
26. A. K. Jana and S. Rajavenii, *Spectrochim. Acta A Mol. Biomol. Spectrosc.*, **60**, 2093 (2004).
27. B. B. Bhowmik and P. Ganguly, *Spectrochim. Acta A Mol. Biomol. Spectrosc.*, **62**, 808 (2005).
28. S. Schreier, S. V. P. Malheiros and E. De Paula, *Biochim. Biophys. Acta - Biomembr.*, **1508**, 210 (2000).
29. R. J. Hunter, *Foundations of colloid science*, 2nd Ed., Oxford University Press, Oxford (2001).
30. C. Tanford, *The hydrophobic effect. The formation of micelles and biological membranes*, 2nd Ed., Wiley, New York (1987).
31. Q. F. Wu, T. Zhang, Z. Li, H. L. Hong, K. Yin, J. S. Jean and W. T. Jiang, *Mater. Technol.*, **29**, B100 (2014).
32. S. Kundu, S. Panigrahi, A. Pal, S. K. Ghosh, S. Nath, S. Praharaj, S. Basu and T. Pal, *Dyes Pigm.*, **69**, 177 (2006).
33. V. Kuban, J. Hedbavny, I. Jancarova and M. Vrchlabsky, *Collect Czech Chem. Commun.*, **54**, 622 (1989).
34. S. Göktürk and R. Y. Talman, *J. Solution Chem.*, **37**, 1709 (2008).
35. S. Mahbub, K. A. A. Shamima, M. A. Rub, M. A. Khan, M. A. Hoque and A. M. Asiri, *Russian J. Phys. Chem. A*, **93**, 2718 (2019).
36. S. Aktar, M. R. Molla, S. Mahbub, M. A. Rub, M. A. Hoque and D. M. S. Islam, *J. Dispers. Sci. Technol.*, **40**, 574 (2019).
37. M. S. Ramadan, N. M. El-Mallah, G. M. Nabil and S. M. Abd-Elmenem, *J. Dispers. Sci. Technol.*, **40**, 1110 (2019).
38. M. Enache, A. M. Toader and M. I. Enache, *Molecules*, **21**, 1 (2016).
39. M. Enache, A. M. Toader, V. Neacsu, G. Ionita and M. I. Enache, *Molecules*, **22**, 1079 (2017).
40. M. Usman, M. A. Rashid, A. Mansha and M. Siddiq, *Thermochim. Acta*, **573**, 18 (2013).
41. A. El Dali, A. El Hashani, K. M. Elsherif and S. Alsherkcy, *Int. J. Chem. Mater. Res.*, **3**, 112 (2015).
42. M. N. Islam and T. Kato, *J. Phys. Chem.*, **107**, 965 (2003).
43. W. Kauzmann, *Adv. Protein Chem.*, **14**, 1 (1959).
44. C. K. Bahal and H. B. Kostenbauder, *J. Pharm. Sci.*, **53**, 1027 (1964).
45. S. Mahbub, M. A. Rub, M. A. Hoque and M. A. Khan, *J. Phys. Org. Chem.*, **31**, e3872 (2018).
46. M. R. Molla, M. A. Rub, A. Ahmed and M. A. Hoque, *J. Mol. Liq.*, **238**, 62 (2017).
47. Kabir-ud-Din, S. Khatoon and A. Z. Naqvi, *Acta Phys. - Chim. Sin.*, **24**, 1180 (2008).
48. K. S. Sharma and A. K. Rakshit, *J. Surfactants Deterg.*, **7**, 305 (2004).
49. G. C. Kresheck, in *Water: A comprehensive treatise*, F. Franks Ed., Plenum Press, New York (1975).
50. S. Mahbub, M. L. Mia, T. Roy, P. Akter, A. K. M. R. Uddin, M. A. Rub, M. A. Hoque and A. M. Asiri, *J. Mol. Liq.*, **297**, 111583 (2020).
51. M. R. Amin, S. Mahbub, S. Hidayathulla, M. M. Alam, M. A. Hoque and M. A. Rub, *J. Mol. Liq.*, **269**, 417 (2018).
52. R. Lumry and S. Rajender, *Biopolymers*, **9**, 1125 (1970).
53. L.-J. Chen, S.-Y. Lin and C.-C. Huang, *J. Phys. Chem. B*, **102**, 4350 (1998).
54. C. Jolicoeur and P. R. Philip, *Can. J. Chem.*, **52**, 1834 (1974).
55. S. Chauhan, J. Jyoti, K. Sharma and K. Kumar, *Fluid Phase Equilib.* **375**, 286 (2014).
56. L.-J. Chen, S.-Y. Lin, C.-C. Huang and E.-M. Chen, *Colloids Surf. A.*, **135**, 175 (1998).
57. M. Rahman, M. A. Rub, M. A. Hoque, M. A. Khan and A. M. Asiri, *J. Mol. Liq.*, **312**, 113366 (2020).
58. M. A. Rahim, S. Mahbub, S. M. A. Ahsan, S. Rana, M. A. Rub, M. A. Hoque, S. E. Kabir and A. M. Asiri, *J. Chem. Eng. Data*, **64**, 5999 (2019).
59. R. Heusch, *BTF: Biotec-Forum*, **3**, 1 (1986).
60. M. A. R. Khan, M. R. Amin, M. A. Rub, M. A. Hoque, M. A. Khan and A. M. Asiri, *J. Chem. Eng. Data*, **64**, 668 (2019).
61. J. Parikh, J. Rathore, D. Bhatt and M. Desai, *J. Dispersion Sci. Technol.*, **34**, 1392 (2013).
62. S. Mahbub, M. A. Rub and M. A. Hoque, *J. Chem. Eng. Data*, **64**, 4181 (2019).
63. M. Rahman, M. A. Hoque, M. A. Khan, M. A. Rub and A. M. Asiri, *Chin. J. Chem. Eng.*, **26**, 1110 (2018).
64. T. M. Perger and M. Bešter-Rogač, *J. Colloid Interface Sci.*, **313**, 288 (2007).
65. A. Pan, T. Kar, A. K. Rakshit and S. P. Moulik, *J. Phys. Chem. B*, **120**, 10531 (2016).

Supporting Information

Spectroscopic and cloud point studies of the interaction and thermodynamics of ciprofloxacin hydrochloride+surfactants mixture in different solvents: Effect of temperature and composition

Md. Anamul Hoque[*,†], Md. Mofaqkharur Rahman[*], Shamim Mahbub[**], Mezbah Hossain[***], Mohammed Abdullah Khan[*], Md. Ruhul Amin[*,], Ali S. Alqahtani[****], Mohammad Z. Ahmed[****,†], Mohammed S. Alqahtani[*****], and Omar M. Almarfadi[****]**

*Department of Chemistry, Jahangirnagar University, Savar, Dhaka- 1342, Bangladesh
**Department of Chemistry & Physics, Gono Bishwabidyalay, Savar, Dhaka- 1344, Bangladesh
***Department of Chemistry, Hajee Mohammad Danesh Science & Technology University, Dinajpur- 5200, Bangladesh
****Department of Pharmacognosy, College of Pharmacy, King Saud University, PO Box 2457, Riyadh 11451, Saudi Arabia
*****Department of Pharmaceutics, College of Pharmacy, King Saud University, Riyadh 11451, Saudi Arabia
(*Received 22 June 2020 • Revised 8 March 2021 • Accepted 16 March 2021*)

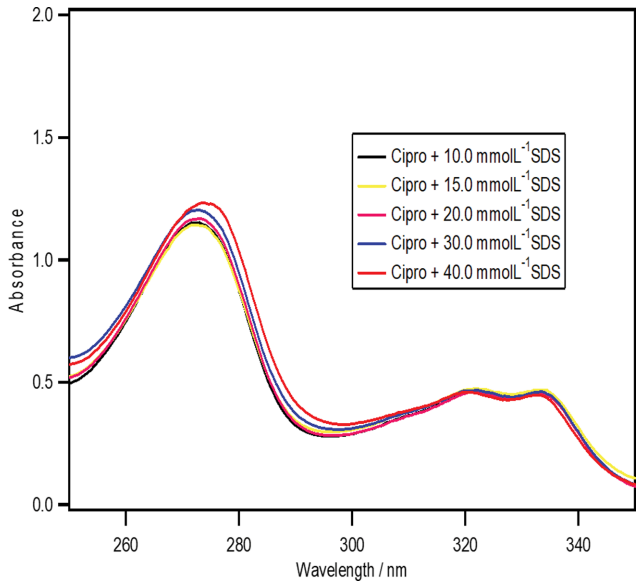


Fig. S1. Absorption spectra for CFH+SDS system in aqueous 10% (v/v) methanol medium having CFH concentration of 4.0× 10^{-5} M at 293.15 K.

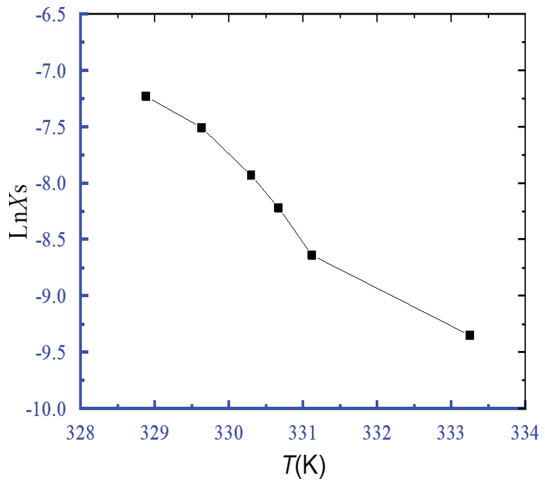


Fig. S2. A representative plot of $\ln X_s$ versus T_{CP} (K) for CFH+TX-100 in $ZnSO_4 \cdot 7H_2O$ solution.

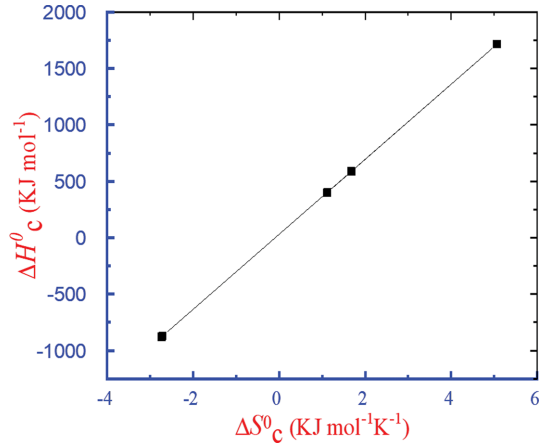


Fig. S3. A representative plot of ΔH_c^0 vs. ΔS_c^0 for the clouding process of TX-100+CFH mixture in aqueous $ZnSO_4 \cdot 7H_2O$ solution.