

## Acetone as a Modulator of Surfactant Behavior in Mixed Solvents: Surface Tension, Viscosity, and Micellization

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### Abstract

This study investigates the influence of acetone on the physicochemical characteristics of surfactants, focusing on surface tension, viscosity, and micellization behavior in acetone-water mixtures. The critical micelle concentration (CMC) of Sodium dodecyl sulfate (SDS) and Cetyltrimethylammonium bromide (CTAB) increases with acetone content, reflecting weaker hydrophobic interactions due to the reduced dielectric constant of the mixed solvent. Surface tension measurements reveal decreased surfactant efficiency in acetone-rich environments, while viscosity data indicate enhanced solute-solvent interactions, as evidenced by rising  $B$  values. These changes are attributed to acetone's disruption of water's hydrogen-bond network, altering interfacial dynamics and micelle formation.

**Keywords:** Acetone-water mixtures; Surfactants; Critical micelle concentration; Viscosity coefficient; Surface tension; Solute-solvent interactions; Micelle formation

### Introduction

Surfactants are amphiphilic molecules with hydrophobic tails and hydrophilic heads, enabling them to adsorb at interfaces and reduce interfacial tension. Their ability to form micelles at the critical micelle concentration (CMC) and self-organize into various structures underpins their applications in detergents, emulsifiers, drug delivery systems, and industrial processes [1]. These properties are significantly influenced by the solvent environment, with mixed solvent systems like acetone-water [2,3] offering tunable parameters such as polarity and dielectric constant that affect surfactant behavior. Mixed solvent systems like acetone-water [2,3] or alcohol-water [4–12] mixtures provide a valuable framework for modulating surfactant behavior through tunable parameters like polarity, viscosity, and dielectric constant. Adding methyl or ethyl alcohol to water decreases the dielectric constant, weakening hydrophobic interactions

and increasing surfactant CMC [7,13–15]. These solvents significantly impact micellization and surface properties. Studies have shown that mixed solvents significantly affect not only the micellization process but also key surface properties. As reported, the surface tension decreases with surfactant concentration, but the slope of this decrease is altered in mixed solvent systems due to variations in molecular packing at the interface and the solvent structure itself [16]. Similarly, viscosity measurements in mixed solvents reveal important solute-solvent interactions, which are critical for understanding the thermodynamic and structural properties of micellar systems [17,18]. Mixed solvent systems have practical applications, including designing surfactant-based formulations for enhanced solubilization, controlled drug release, and improved emulsion stability. Alcohol-water studies, such as SDS in methanol-water mixtures, show a systematic CMC increase with methanol content due to

reduced hydrophobic effects and altered solvent dynamics. Variations in surfactant packing parameters suggest changes in micellar geometry, such as spherical-to-rod-like transitions, influencing viscosity and phase behavior [19]. Acetone-water system show significant non-linear deviations from ideality due to strong molecular interactions like hydrogen bonding, affecting density, surface tension, viscosity and refractive index. Fully miscible, this system is crucial in chemical and industrial process like extraction, distillation and solvent applications [20–22].

Viscometric studies reveal solute-solvent interactions, with the viscosity B coefficient from the Jones-Dole equation quantifying interaction strength. A larger positive B value indicates solute-induced solvent structuring. A previous study found that methanol increases viscosity and CMC of cationic surfactants by affecting the dielectric constant and hydrophobic interactions. B coefficients rise with methanol concentration but decrease with temperature, indicating stronger interactions in methanol-rich media [23].

While alcohol-water systems have been extensively studied [4–12], the role of acetone as a solvent remains underexplored. Acetone disrupts water's hydrogen-bond network more significantly than alcohols, leading to unique changes in surface tension, viscosity, and micellization. This article explores surface tension (ST) and viscosity (VS) of surfactants in acetone-water mixtures using the Man Singh survismeter, a compact glass device that combines both measurements in one tool. Its innovative design enhances efficiency and precision, particularly in studying molecular interactions like hydrophilic-hydrophobic behaviors. The survismeter provides accurate results with minimal deviations, making it valuable for applications in biochemical and industrial research [24,25].

## Materials and Methods

Cetyltrimethylammonium bromide (CTAB)

and sodium dodecyl sulfate (SDS) both having 99.0% pure were procured from Loba Chemie Pvt. Ltd., Mumbai, India. Both surfactants were utilized as received, without any additional purification and were pre-heated at 100°C for 1 hour prior to use to ensure removal of any absorbed moisture. Acetone (99.0% pure) was obtained from E. Merck, India. Doubly distilled water ( $\kappa < 0.6 \mu S/cm$ ) was used to prepare all the solvent mixtures of acetone-water and surfactant solutions at 298.15 K.

The acetone-water mixtures were prepared by carefully measuring and mixing acetone and distilled water in varying molar percentages. Surfactant stock solutions were made by dissolving precisely weighed amounts of surfactant in acetone-water mixtures of desired compositions. Solutions were stored in air-tight containers to minimize contamination and evaporation.

Surface tension and viscosity measurements were performed using a Borosil Mansingh Survismeter [24]. Surface tension was measured using the Pendant Drop Number (PDN) method, while viscosity was measured using the Viscous Flow Time (VFT) method [24, 26]. The instrument was calibrated using methanol. The calibrated values ( $ST = 22.51 mNm^{-1}$  and  $VS = 0.5440 mPa s$ ) were matched with literature data [7].

The PDN method involved counting the number of drops for a given volume of both the solvent and the solution using the Survismeter. Surface tension was calculated using the following formula:

$$\gamma_{soln} = \left( \frac{n_{soln}}{n_{solv}} \right) \left( \frac{d_{soln}}{d_{solv}} \right) \gamma_{solv} \quad (1)$$

where,

$\gamma_{soln}$  and  $\gamma_{solv}$  are STs of solution and solvent respectively.

$n_{soln}$  and  $n_{solv}$  are drop numbers of

solvent and solution respectively.

$d_{\text{soln}}$  and  $d_{\text{solv}}$  are densities of solution and solvent respectively.

Viscosity was determined by recording the flow time of a fixed volume of solution through a calibrated capillary tube in the Survisometer. The subsequent equation was used to compute viscosity:

$$\eta_{\text{soln}} = \left(\frac{t_{\text{soln}}}{t_{\text{solv}}}\right) \left(\frac{d_{\text{soln}}}{d_{\text{solv}}}\right) \eta_{\text{solv}} \quad (2)$$

where,

$\eta_{\text{soln}}$  and  $\eta_{\text{solv}}$  are viscosities of solution and solvent respectively.

$t_{\text{solv}}$  and  $t_{\text{soln}}$  are flow times of solvent and solution respectively.

$d_{\text{soln}}$  and  $d_{\text{solv}}$  are density of solution and solvent respectively.

The densities required for the calculations were measured using a 25 cm<sup>3</sup> pycnometer [27]. The pycnometer was filled with the solution, sealed, and submerged in a thermostat-controlled water bath to maintain a constant temperature. After thermal equilibrium was achieved, the mass was determined using an electronic balance with a correctness of  $\pm 0.0001$  g. Densities were calculated with a precision of  $\pm 0.00005$  g/cm<sup>3</sup>.

## Results and Discussion

**Table 1** outlines the density, viscosity, surface tension, and dielectric constant of acetone-water mixtures at varying acetone mole percentages. These properties exhibit significant deviations from ideal behavior due to the complex molecular interactions between acetone and water, primarily hydrogen bonding and dipole-dipole interactions. **Figs 1** and **2** illustrates the variation of ST with log [CTAB] in acetone-water mixtures at varying mole%. Similar graphs were obtained for SDS (not shown here). The data highlights how solvent composition affects the surface activity of

surfactant, particularly the CMC and pre-micellar slopes. In **Fig. 1**, the CMC is identified as the inflection point where ST ceases to decrease with increasing surfactant concentration. For CTAB in pure water (0 mol% acetone), the CMC is relatively low due to strong hydrophobic interaction in the highly polar solvent. Similarly, SDS shows a lower CMC under same conditions, but the absolute value is higher than that of CTAB, reflecting the weaker micelle-forming tendency of SDS in water.

**Table 1.** Physical properties of acetone-water mixed solvent media (ACT= acetone)

Mol% of ACT	Density ( $\rho$ ) (g/cc)	Viscosity ( $\eta$ ) (cp)	Surface Tension ( $\gamma$ ) (mNm <sup>-1</sup> )	Dielectric constant [22,28]
0.00	0.9970 [29]	0.8931 [30]	71.99	80.40
2.65	0.9866	1.0635	55.10	75.42
5.77	0.9744	1.2214	44.17	71.47
9.50	0.9609	1.3307	38.09	67.22
14.04	0.9457	1.3769	35.76	71.9

The steep reduction in ST before CMC indicates effacing adsorption of surfactant molecules at the air/solution interface for both surfactants. In **Fig. 2**, the pre-micellar slope, representing the rate of ST reduction with increasing surfactant concentration before the CMC [16], declines as acetone concentration increases. For both SDS and CTAB, this slope is steepest in pure water, highlighting strong hydrophobic interactions and efficient surfactant adsorption. In acetone rich mixtures, the slope becomes progressively shallower, with SDS showing a sharper decline compared to CTAB. This behavior is attributed to acetone's ability to disrupt the hydrogen-bond network of water and compete for interfacial space.

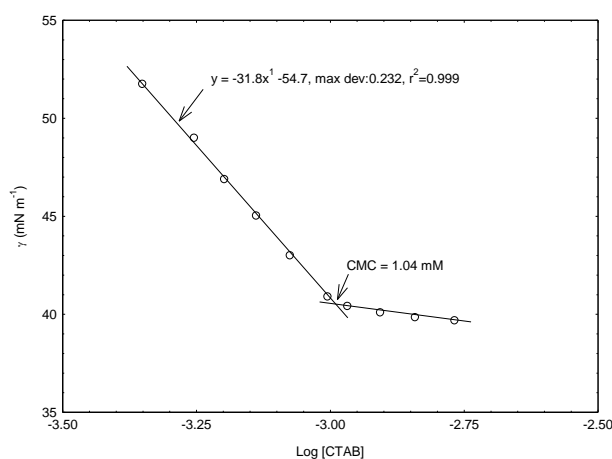
**Table 2** and **3** summarizes CMC values of SDS and CTAB by ST and VS measurements across varying acetone mole fraction, demonstrating clear increase in CMC with higher acetone content for both surfactants. SDS show more pronounced increase in CMC compared to CTAB, indicating greater sensitivity

to changes in solvent polarity. This trend reflects acetone's impact on hydrophobic interactions, as the reduction in the solvent's dielectric constant weakens these forces, delaying micelle formation [31]. The pre-micellar slope in **Fig. 2**, representing the rate of ST reduction before reaching the CMC [16], decreases with higher acetone content. In pure water, the steep slope reflects the efficient adsorption of surfactant molecules at the air-aqueous boundary, driven by strong hydrophobic interactions and a high dielectric constant. As acetone concentration increases, the slope becomes progressively shallower. This behavior is attributed to acetone's role in disrupting the structured hydrogen-bond network of water and competing for the interfacial space [31]. Acetone molecules reduce the cohesive forces at the interface and weaken hydrophobic interactions, making surfactants less effective in reducing surface tension. The decline in slope highlights the reduced surface activity of surfactants in acetone-rich environments, suggesting that acetone modulates the interfacial dynamics and adsorption efficiency of surfactants. This trend has implications for the design of surfactant systems in mixed solvents, where reduced pre-micellar efficiency might necessitate higher surfactant concentrations for effective surface tension control.

### Critical Micelle Concentration (CMC)

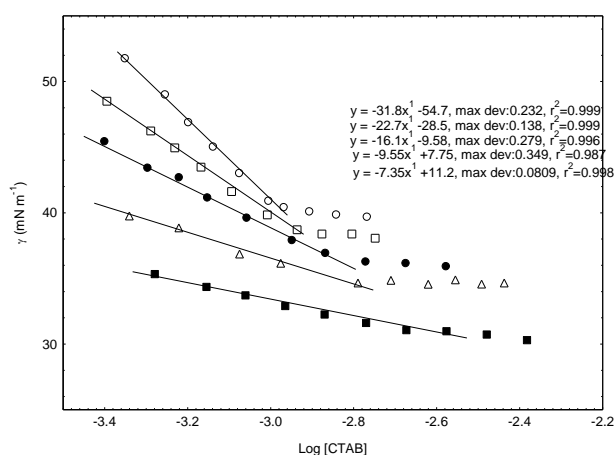
The effect of acetone on the CMC of surfactants, as obtained by surface tension (ST) and viscosity (VS) measurements (**Tables 2 and 3**), reveals a consistent trend of increasing CMC with higher acetone concentrations. For both CTAB and SDS, the CMC values derived from surface tension data correspond to the point of inflection where further surfactant addition no longer reduces surface tension significantly,

marking the onset of micelle formation. Similarly, viscosity measurements provide complementary insights, as the CMC is identified by a distinct change in the viscosity curve due to the transition from monomeric surfactant behavior to micelle formation [18].



**Fig. 1.** Change of surface tension with log [CTAB] showing CMC and slope at 298.15 K.

In acetone-water mixtures, the CMC increases systematically with acetone mole percentage, indicating that the reduced dielectric constant of the solvent weakens hydrophobic interactions, a key driving force for micelle formation.



**Fig. 2.** Change of surface tension of CTAB with log [CTAB] in water (o) and in various mol% (2.65(□), 5.77(●), 9.50(Δ), and 14.04(■)) of acetone-water at 298.15 K.

This behavior is consistent across both

measurement techniques, affirming that acetone disrupts the solvent's polar structure, making micellization less thermodynamically favorable. The complementary nature of surface tension and viscosity methods underscores the reliability of these findings, with both demonstrating that acetone significantly modulates the aggregation behavior of surfactants in mixed solvent systems.

Surface properties: Surface properties viz., surface excess concentration ( $\Gamma_{\max}$ ), smallest area covered by surfactant molecule ( $A_{\min}$ ), surface pressure ( $\pi_{\text{cmc}}$ ) are calculated by equations (3) to (5) [11,12,14].

$$\Gamma_{\max} = -\frac{1}{2.303nRT} \left[ \frac{d\gamma}{d \log C} \right]_{T,P} \quad (3)$$

$\frac{d\gamma}{d \log C}$  is premicellar slope of plot between  $\gamma$  and logarithm of concentration of surfactant solution.  $R$  ( $8.314 \text{ J mol}^{-1} \text{ K}^{-1}$ ) is universal gas constant.  $n = 2$  for conventional ionic surfactants.

$$A_{\min} = 1/N_A \Gamma_{\max} \quad (4)$$

$$\pi_{\text{cmc}} = \gamma_0 - \gamma_{\text{cmc}} \quad (5)$$

where  $\gamma_{\text{cmc}}$  and  $\gamma_0$  represent ST at the CMC and of solvent respectively.

Micellar packing parameter is given by equation (6), the value of which represents the information about micellar geometry.

$$P = \frac{V_0}{A_{\min} l_c} \quad (6)$$

where  $V_0$  is given by Tanford's formula,  $V_0 = [27.4 + 26.9(n_c - 1)]2\text{\AA}^3$ ,  $l_c = [1.54 + 1.26(n_c - 1)]\text{\AA}$ .  $l_c$  and  $n_c$  represent the maximum chain length and the number of carbon atoms in the hydrocarbon chain respectively. **Tables 2 and 3** present key surface properties of SDS and CTAB in acetone-water mixtures, including excess surface concentration ( $\Gamma_{\max}$ ), minimum area per molecule ( $A_{\min}$ ), surface pressure at the CMC ( $\pi_{\text{cmc}}$ ). The excess concentration ( $\Gamma_{\max}$ ), an extent of the amount of surfactant adsorbed at the

interface, decreases as the acetone content increases. For both SDS and CTAB,  $\Gamma_{\max}$  is highest in pure water, reflecting the strong adsorption efficiency driven by water's high polarity and robust hydrophobic interactions. In acetone-water mixtures,  $\Gamma_{\max}$  decreases, indicating reduced surfactant adsorption at the interface. Acetone molecules disrupt water's hydrogen-bond network and occupy interfacial sites, thereby competing with surfactants and reducing their effective packing density.

**Table 2.** CMC and surface properties ( $\Gamma_{\max}$ ,  $A_{\min}$ ,  $\pi_{\text{cmc}}$  and  $P$ ) of SDS in water and various mol% of acetone-water at 298.15 K.

Mol% of ACT	CMC / mM		$\Gamma_{\max} 10^6$ ( $\text{mol m}^{-2}$ )	$A_{\min}$ ( $\text{\AA}^2 \text{ molecule}^{-1}$ )	$\pi_{\text{cmc}}$ ( $\text{mN m}^{-1}$ )	$P$
	ST	VS				
0.00	8.27	8.01	2.03	81.72	31.18	0.26
2.65	10.49	10.22	1.25	132.58	16.48	0.16
5.77	14.41	13.98	0.72	231.50	7.96	0.09
9.50	15.54	15.51	0.53	312.35	3.77	0.07
14.04	19.92	19.76	0.52	317.05	5.08	0.07

Errors in  $\Gamma_{\max} 10^6$ ,  $A_{\min}$ ,  $\pi_{\text{cmc}}$ ,  $P$  are within  $\pm 3$ ,  $\pm 3$ ,  $\pm 5$ ,  $\pm 4\%$  respectively. ACT = Acetone

The minimum area per molecule ( $A_{\min}$ ), calculated as the reciprocal of  $\Gamma_{\max}$ , increases with acetone content. This reflects less compact packing of amphiphiles at the interface in acetone-rich mixtures. In pure water, surfactant molecules achieve tight packing due to strong interfacial interactions. However, the introduction of acetone reduces these interactions, leading to larger interfacial areas per surfactant molecule. For instance, SDS and CTAB show significantly larger  $A_{\min}$  in higher acetone concentrations, emphasizing acetone's role in altering interfacial structure.

Surface pressure at the CMC ( $\pi_{\text{cmc}}$ ), defined as the difference between the ST of the pure solvent and that at the CMC, also decreases with increasing acetone content. This trend underscores the reduced ability of surfactants to lower surface tension in acetone-rich environments. The less polar nature of acetone-water mixtures weakens the surfactant's impact

on interfacial cohesion, resulting in lower surface pressure values at the CMC.

The packing parameter ( $P$ ) offers a quantitative framework to understand the structural changes in surfactant aggregates in acetone-water systems. The observed decrease in  $P$  with increasing acetone concentration underscores the solvent's role in modulating micelle shape and surface behavior, providing a basis for optimizing surfactant formulations in mixed solvent environments.

**Table 3.** CMC and surface properties ( $\Gamma_{\max}$ ,  $A_{\min}$ ,  $\pi_{\text{cmc}}$  and  $P$ ) of CTAB in water and various mol% of acetone-water at 298.15 K

Mol% of ACT	CMC / mM		$\Gamma_{\max} 10^6$ ( $\text{mol m}^{-2}$ )	$A_{\min}$ ( $\text{\AA}^2 \text{ molecule}^{-1}$ )	$\pi_{\text{cmc}}$ ( $\text{mN m}^{-1}$ )	$P$
	ST	VS				
0.00	1.04	0.99	2.79	59.62	35.34	0.35
2.65	1.17	1.11	1.99	83.52	20.23	0.25
5.77	1.49	1.41	1.41	117.76	10.98	0.18
9.50	1.99	1.89	0.84	198.53	5.81	0.11
14.04	2.28	2.21	0.64	257.95	4.85	0.08

Errors in  $\Gamma_{\max} 10^6$ ,  $A_{\min}$ ,  $\pi_{\text{cmc}}$ ,  $P$  are within  $\pm 3$ ,  $\pm 3$ ,  $\pm 5$ ,  $\pm 4\%$  respectively (ACT= acetone).

Viscosity  $B$  coefficients: The viscosity  $B$  coefficient, as presented in the Jones-Dole equation (equation 7) of viscosity, effectively characterizes the interaction between solvent and solute. [32–34].

$$\eta_r = 1 + A\sqrt{c} + Bc \quad (7)$$

where,  $\eta_r = \eta/\eta_0$  is identified as relative viscosity.

On arranging equation (7)

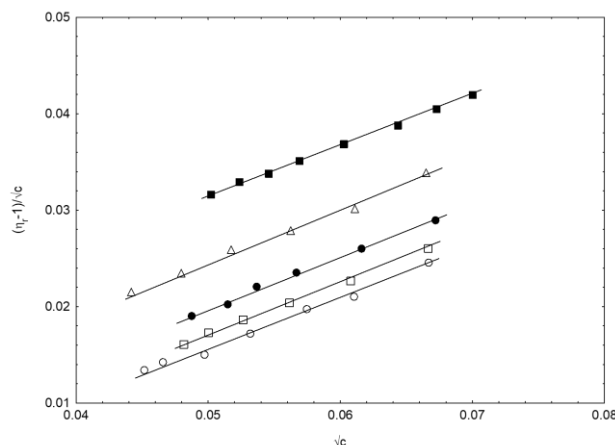
$$\frac{(\eta_r - 1)}{\sqrt{c}} = A + B\sqrt{c} \quad (8)$$

The constants  $B$  and  $A$  accounts for solute – solvent and solute – solute interactions, respectively [35].

The study of viscosity plays a crucial role in understanding solute-solvent interactions, which are key to explaining the properties of microemulsions and liquid crystals in relation to micellar solutions of surfactant systems. In such systems, the interactions between

surfactants and solvents are particularly significant, involving two primary interactions: the solvent's interaction with the hydrophobic (tail) region and its interaction with the hydrophilic (head) region of surfactant molecules. These interactions influence the viscous flow of the liquid, leading to changes in several physicochemical characteristics [17,18,35].

The viscosity coefficient ( $B$ ), derived from the Jones-Dole equation, obtained as a slope of plot (Fig. 4), quantifies solute-solvent interactions in acetone-water mixtures. Data from Table 4 show that  $B$  -values for both SDS and CTAB increase with higher acetone concentrations, indicating enhanced interactions between surfactants and the mixed solvent. SDS exhibits a more pronounced increase in  $B$  compared to CTAB, reflecting stronger interactions between acetone and SDS's anionic head group. This trend arises because acetone disrupts water's hydrogen-bond network, creating a less cohesive medium that enhances localized solvation around surfactants.



**Fig. 3.** Variation of  $\frac{(\eta_r - 1)}{\sqrt{c}}$  with  $\sqrt{c}$  of CTAB in water (o) and in various mol% (2.65( $\square$ ), 5.77( $\bullet$ ), 9.50( $\Delta$ ), and 14.04( $\blacksquare$ )) of acetone-water at 298.15 K

The rise in  $B$  values with acetone concentration is attributed to acetone's ability to

disrupt water's hydrogen-bond network, leading to enhanced solvation around the surfactant molecules. These changes indicate that acetone modifies the solute-solvent dynamics, increasing viscous resistance in the solution and emphasizing its role in tailoring the viscosity of surfactant systems.

**Table 4.** Viscosity  $B$  coefficient of SDS and CTAB in water and various mol% of ACT Error in  $B$  is within  $\pm 4\%$  (ACT =acetone)

Mol% ACT	SDS	CTAB
0.00	+3.46	+0.515
2.65	+5.65	+0.527
5.77	+5.92	+0.539
9.50	+6.72	+0.540
14.05	+7.11	+0.546

**Error in  $B$  is within  $\pm 4\%$ .**

## Conclusions

The study highlights the significant impact of acetone on the physicochemical properties of surfactants in acetone-water mixtures. Key findings include increased critical micelle concentrations (CMC) and reduced surface activity with higher acetone content, attributed to weakened hydrophobic interactions and altered interfacial dynamics. The viscosity coefficient ( $B$ ) also increases with acetone concentration, reflecting enhanced solute-solvent interactions due to acetone's disruption of water's hydrogen-bond network. These results underscore acetone's role in modulating surface and micellar properties, providing valuable insights for optimizing surfactant-based formulations in diverse industrial and pharmaceutical applications, particularly where precise control over interfacial and solution properties is required.

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## Author's Contribution Statement

**Sujit Kumar Shah** : Conceptualization, Data curation, Writing -original draft, Formal analysis, Investigation, **Geeta Bhattarai**: Methodology, Project administration, Visualization., **Ajaya Bhattarai**: Supervision, Resources, Software, Funding acquisition Validation, Writing – review & editing.

## Conflict of Interest

The authors do not have any conflict of interest throughout this research work.

## Data Availability Statement

The data supporting this study's findings are available from the corresponding authors upon reasonable request.

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