

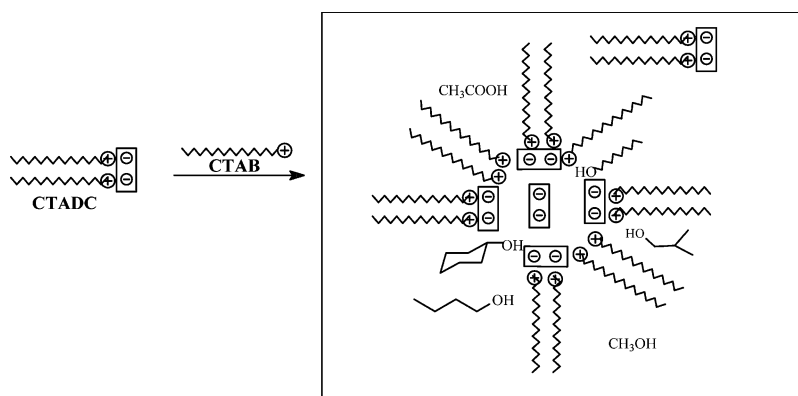
Oxidation of Alcohol by Lipopathic Cr(VI): A Mechanistic Study

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The oxidation kinetics of various aliphatic primary and secondary alcohols having varied hydrocarbon chain length were studied using cetyltrimethylammonium dichromate (CTADC) in dichloromethane (DCM) in the presence of acetic acid and in the presence of a cationic surfactant. The rate of the reaction is highly sensitive to the change in [CTADC], [alcohol], [acid], [surfactant], polarity of the solvents, and reaction temperature. A Michaelis–Menten type kinetics was observed with respect to substrate. The chemical nature of the intermediate and the reaction mechanism were proposed on the basis of (i) observed rate constant dependencies on the reactants, that is, fractional order with respect to alcohol and acid and a negative order with respect to oxidant, (ii) high negative entropy change, (iii) inverse solvent kinetic isotope effect, $k(\text{H}_2\text{O})/k(\text{D}_2\text{O}) = 0.76$, (iv) low primary kinetic isotope effect, $k_{\text{H}}/k_{\text{D}} = 2.81$, and (v) the k_{obs} dependencies on solvent polarity parameters. The observed experimental data suggested the self-aggregation of CTADC giving rise to a reverse micellar system akin to an enzymatic environment, and the proposed mechanism involves the following: (i) formation of a complex between alcohol and the protonated dichromate in a rapid equilibrium, equilibrium constant $K = 5.13 (\pm 0.07) \text{ dm}^3 \text{ mol}^{-1}$, and (ii) rate determining decomposition ($k_2 = (7.6 \pm 0.7) \times 10^{-3} \text{ s}^{-1}$) of the ester intermediate to the corresponding carbonyl compound. The effect of [surfactant] on the rate constant and the correlation of solvent parameters with the rate constants support the contribution of hydrophobic environment to the reaction mechanism.

Introduction

An onium ion, as the counterion for anionic oxidants, makes a lot of difference in oxidation potential of the oxidant as well as to the oxidizing system. It makes the oxidant lipid soluble, mild, and many a time chemoselective. Tailor-made oniums have been used as the counterions wherein heterocyclic bases such as pyridine,¹ quinoline,² caffeine,³ imidazole,⁴ and nicotine⁵ units become a part of the oxidant. In different reaction conditions, sometimes these oxidants show biomimetic character-

istics due to the counterions providing a micro-heterogeneous environment with different solubilization pockets for the substrates as in the case of micelles, reversed micelles, micro-emulsions, vesicles for artificial systems, and proteins and lipid membranes in living systems.⁶ Among these oxidants, Mn(VII) and Cr(VI) have been studied extensively.

For Mn(VII), the onium ions are mostly due to symmetrical tetraalkylammonium ions.⁷ There are also reports of unsymmetrical tetraalkylammonium ions^{7,8} such as benzyltriethylammonium, methyltri-*n*-octylammonium, and cetyltrimethyl-

ammonium ions as the counterions which carry Mn(VII) oxidant to the lipid system (organic solvents). Dash and Mishra⁹ have reported the product specificity of cetyltrimethylammonium permanganate (CTAP) in a chloroform medium for olefinic double bonds. The cis compounds are converted to the corresponding diols, whereas the trans compounds lead to cleavage of the double bond. However, CTAP is found to be a self-destructor and may be considered as a suicidal oxidant. The Mn(VII) oxidizes the carrier cetyltrimethylammonium ion to hexadecanal in a mechanism akin to β -oxidation of fatty acids by corresponding dehydrogenase.¹⁰

A large number of Cr(VI) oxidants with onium ions have been reported, among which pyridinium chlorochromate (PCC)^{1a} has attracted the attention of synthetic chemists the most. Its versatility is due to the commercial availability, efficiency, and self-stability. The anionic species in these types of oxidants is either a chromate or a dichromate. Most of these reagents contain one acidic hydrogen (pH of a 0.01 M solution of PCC, PFC (pyridinium fluorochromate), QFC (quinolinium fluorochromate), and DmpzHFC (3,5-dimethylpyrazolium fluorochromate) were found to be 1.75, 2.45, 3.35, and 4.9, respectively, and the corresponding pK_a values were 1.4, 2.7, 4.7, and 7.8, respectively),¹¹ which in some cases is sufficient to enable the oxidative transformation and which in some cases creates a problem for the oxidation of compounds containing acid sensitive functionality.

In a continuation of our efforts to explore some biomimetic oxidants to oxidize organic substrates in organic solvents, we have reported the oxidation behavior of cetyltrimethylammonium dichromate (CTADC)^{6,12} toward various organic

substrates. This reagent is water insoluble and stable at room temperature for more than a year when kept in sealed bottle. Although Cr(VI) is undisputedly carcinogenic, the insolubility in water reduces contamination of Cr(VI) in aqueous medium, and the compound thus can be used as a green reagent. Further, CTADC is devoid of an acidic proton and thus is relatively milder than other Cr(VI) oxidants. In the absence of acid, CTADC exhibits some bizarre reactions with nonconventional products. Aromatic amines are found to yield corresponding diazo compounds,^{12a} and arylaloximes yielded corresponding nitriles.^{12c} Recently, in an oxidation reaction of cholesterol with CTADC, we have observed that 7-dehydrocholesterol is obtained instead of cholestenone.⁶ This dehydrogenation is a rare event in Cr(VI) oxidation studies, and it is explained through a remote functionalization mechanism. In this mechanism, the cetyltrimethylammonium ion provides a conducive environment for proper orientation of the oxochromium group so that the removal of hydrogen becomes easier.

However, in the presence of acid, arylaloximes and ketoximes produced carbonyl compounds with CTADC. Further, the protonated dichromate oxidizes the secondary hydroxy group of cholesterol to the corresponding ketone on the addition of acid. The reaction kinetics reveals that the reaction system resembles that of cholesterol oxidase, which carries FAD as the dehydrogenating agent in the enzyme and oxidizes cholesterol to corresponding cholestenone. In an analogy to this system, CTADC in an organic solvent like DCM forms a reversed micelle where the dichromate is encapsulated by the cationic oniums and cholesterol is partitioned into the mesophase.⁶

To have more insight into the contribution of the hydrophobicity of the substrate to the reaction mechanism, a series of alcohols have been used, in the present study, for the oxidation reaction by CTADC. Further, attempts have been made to provide more evidence for the hydrophobic contribution of the solvents toward the reactivity of CTADC through reverse micellization.

Results and Discussion

The reaction mixture consisting of CTADC, alcohol, and acetic acid in dichloromethane in almost all cases turns to green after completion of the reaction. On chromatographic separation of the reaction mixture, aldehydes and ketones are eluted from the oxidation product. Further the IR characteristic bands of the eluted product at 1710–1725 cm^{-1} support the formation of corresponding aldehydes and ketones. It is found that under the experimental condition the carbonyl compounds are not oxidized further.

From the stoichiometric analysis, it is found that 1 mole equiv of CTADC reacts with 3 mole equiv of alcohols, and thus the ratio of Cr(VI)/alcohol is found to be 2:3. During the oxidation process, Cr(VI) is reduced to Cr(IV), which disproportionates with another Cr(VI) to Cr(V). The existence of Cr(IV) as the reduced state in oxidation of alcohol by quinolinium bromochromate has also been reported by Saraswat et al.¹³ Cr(V) is further reduced to Cr(III) by the addition of two electrons. The existence of Cr(III) in the product mixture was established from the absorption maximum at 580 nm.¹⁴

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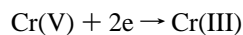
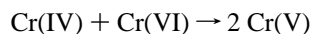
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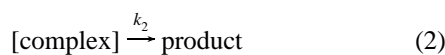
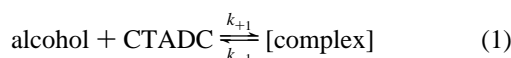


The rate of reaction was monitored by observing the rate of depletion of the peak at 350 nm, and the observed rate constants, k_{obs} , are tabulated in Table 1. The reaction was found to be acid catalyzed, and the k_{obs} obeys the equation

$$k_{\text{obs}} = k_o + k_{\text{cat}}[\text{acetic acid}]$$

where k_o is the uncatalyzed rate constant. For cyclohexanol the value is found to be $2.3 \times 10^{-4} \text{ s}^{-1}$ ($R^2 = 0.9954$), indicating very slow reaction without acid. From the logarithmic plot, the order of the reaction with respect to [AcOH] is determined to be 0.9. The fractional order may be attributed to the extent of protonation of CTADC because of the tight ion pair of CTA^+ and $\text{Cr}_2\text{O}_7^{2-}$ in dichloromethane.

The reaction kinetics is found to obey the Michaelis–Menten equation with respect to [alcohol]; that is, a complex is formed between oxidant and substrate prior to the rate determining step. The complex subsequently decomposes into the products.



Accordingly the rate expression for the reaction is mentioned below.

$$\frac{1}{k_{\text{obs}}} = \frac{1}{k_2 K [\text{alcohol}]} + \frac{1}{k_2} \quad (3)$$

From the plot of k_{obs} against [alcohol] (Figure 1), the Michaelis–Menten constant, K_m , is found to be 0.2 M. By using a Lineweaver–Burk type double reciprocal equation (eq 3) the binding constant $K (= k_{+1}/k_{-1})$ and k_2 are obtained and found to be $5.13 (\pm 0.07) \text{ dm}^3 \text{ mol}^{-1}$ and $7.6 (\pm 0.7) \times 10^{-3} \text{ s}^{-1}$, respectively. The corresponding double reciprocal plot is shown in the inset of Figure 1. From K , K_m , and k_2 values, the k_{+1} and k_{-1} were calculated to be $94.4 (\pm 1.2) \times 10^{-3} \text{ s}^{-1}$ and $18.4 (\pm 0.2) \times 10^{-3} \text{ s}^{-1}$, respectively. Further, the solvent kinetic isotope effect, $k(\text{H}_2\text{O})/k(\text{D}_2\text{O})$, was found to be $(3.5 \times 10^{-4}) / (4.6 \times 10^{-4}) = 0.76$. The acid-catalyzed rate is faster in D_2O than in H_2O when a preequilibrium protonation is involved in the reaction mechanism.¹⁵ The inverse kinetic isotope effect, $k(\text{D}_2\text{O}) > k(\text{H}_2\text{O})$, indicates that the hydroxyl group is not involved either in preequilibrium nor in the rate determining step, which precludes the possibility of breaking an O–H bond in the rate-determining step, and thus supports the formation of a dichromate ester in the reaction process.

To supplement the above findings, the kinetic isotope effect was investigated by using methanol- d_4 as the substrate, and the $k_{\text{H}}/k_{\text{D}}$ was found to be 2.81. In a series of oxidation reactions of aliphatic alcohols by Banerji et al., the isotope effects are found to be 5.68 at 298 K and 5.72 by using quinolinium bromochromate¹³ and pyridinium chlorochromate,¹⁶ respectively, and this value has been attributed to the α -C–H bond cleavage in the rate determining step. The isotope effect of 2.81 in the

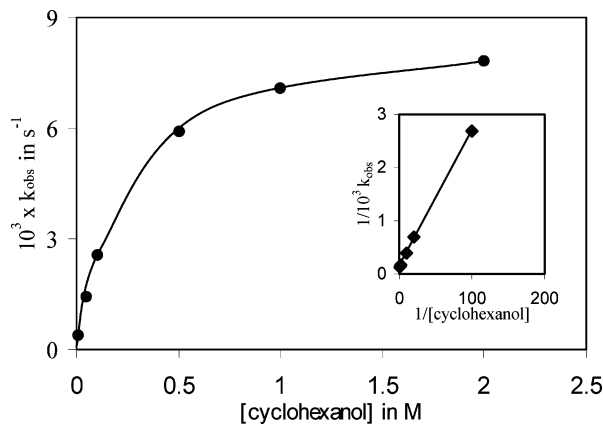


FIGURE 1. Plot of $10^3 k_{\text{obs}}$ versus [cyclohexanol] in the oxidation reaction of CTADC with cyclohexanol at 303 K.

TABLE 1. Effect of [Cyclohexanol], [CTADC] and [Acetic Acid] on the Oxidation of Cyclohexanol by CTADC in DCM at 303 K

[CTADC] $\times 10^4$ M	[cyclohexanol] M	[acetic acid] M	$k_{\text{obs}} \times 10^3$ s^{-1}
0.47	0.5	3.24	9.5
0.94	0.5	3.24	7.4
1.89	0.5	3.24	5.9
2.83	0.5	3.24	4.7
4.70	0.5	3.24	4.1
1.89	0.01	3.24	0.4
1.89	0.05	3.24	1.4
1.89	0.1	3.24	2.5
1.89	1	3.24	7.1
1.89	2	3.24	7.8
1.89	0.5	0.81	1.9
1.89	0.5	1.62	3.6
1.89	0.5	6.48	12.0
1.89	0.5	8.10	15.9

present study also supports the involvement of α -C–H bond breaking in the rate-determining step. However, this small kinetic isotope effect may be explained on the basis of the aforesaid two-step mechanism (eqs 1 and 2). The contribution of the ester formation toward the rate determining step is also significant where there is no primary kinetic isotope effect which diminishes the isotope effect. Long back, Rocek et al.¹⁷ and Lee and Stewart¹⁸ had investigated the kinetic isotope effect of Cr(VI) oxidation of alcohols and had proposed that both ester formation and cleavage of the C–H bond contributed to the rate determining step. They observed a kinetic isotope effect of about 2 and 1.32 for 60% aqueous acetic acid and 95.3% sulfuric acid, respectively.

Consistent with the above observations, a mechanism has been proposed where dichromate ion forms an ester intermediate with alcohol, which subsequently decomposes by α -hydrogen abstraction to a corresponding aldehyde or ketone (Scheme 1).

With increasing concentration of CTADC, the rate constant was found to decrease nonlinearly with a concavity (Table 1). The logarithmic plot of [CTADC] against k_{obs} is found to be linear ($R^2 = 0.99$), and the corresponding order of reaction is found to be 0.364. A fractional order depicts the reaction to follow as a complex mechanism. The decrease in rate constant with increase in [CTADC] may be ascribed to the formation of

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SCHEME 1

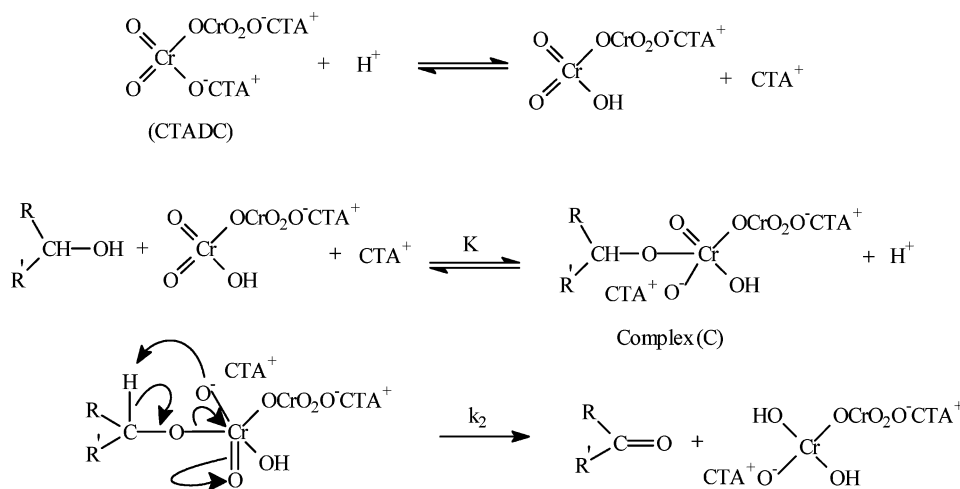


TABLE 2. Effect of [CTAB] in the Observed Rate Constant in the Oxidation of Various Primary Alcohols by CTADC in DCM at 303 K

[CTAB]	$10^3 k_{\text{obs}} \text{ s}^{-1}$							
	methanol	ethanol	1-propanol	1-butanol	1-pentanol	1-hexanol	1-octanol	cyclohexanol
0	0.5	2.6	2.9	3.6	3.9	4.1	4.2	5.9
1×10^{-4}	0.3	2.5	2.3	3.4	3.1	2.8	2.9	4.6
5×10^{-4}	0.2	1.9	1.6	3.3	2.2	2.5	2.0	4.1
1×10^{-3}	0.1	1.3	1.4	2.8	2.0	2.1	1.9	3.6
5×10^{-3}	0.1	0.6	0.5	1.5	1.0	1.0	0.8	1.8
1×10^{-2}	0.1	0.3	0.3	0.6	0.6	0.7	0.5	1.0
2×10^{-2}	0.1	0.2	0.3	0.4	0.4	0.4	0.4	0.8
5×10^{-2}	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.6

reversed micelles wherein the dichromate ion is enveloped by CTA^+ . CTAB forms reversed micelles in DCM providing a cationic interface and a suitable residing site for anions.¹⁹ Alcohols are known to behave as cosurfactants for the formation of a microemulsion, a surfactant aggregate, where the hydroxy group of the alcohols exposed to the interface and the hydrophobic alkyl tail entangles with the mesophase. Although the dichromate and alcohols are in close proximity, in the absence of acetic acid no reaction takes place. Further, [AcOH] versus the rate constant profile envisages that acid catalyzes the reaction. But in CTAB-reversed micellar interface, a proton may not be available for the dichromate, and thus it leads to a decrease in rate. With increasing [CTADC] there may be an increase in reverse micelle formation, and thus a negative trend is inevitable.

To get support for this proposition, the reaction kinetics of CTADC with alcohols was investigated in the presence of cetyltrimethylammonium bromide (CTAB). With an increase in [CTAB], the rate is found to decrease asymptotically (Table 2). This trend may be attributed to the increase in positive charge at the surface, which repels the proton more to the core of the reversed micelle, keeping it away from the reaction site. Above a concentration of 1×10^{-2} M of CTAB, the rate constant almost levels off (Figure 2). Assuming the rate decrease is due only to the partition of the alcohol and protonated Cr(VI), for complete entrapment of a dichromate (2×10^{-4} M) by CTA^+ (1×10^{-2} M) it requires a composition of 1:50 of CTADC/CTAB.

The point of saturation due to the increase in [CTAB] can be determined from the transition point of the bilinear plot of

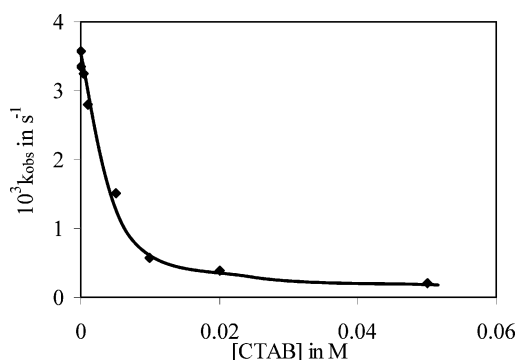


FIGURE 2. Plot of $10^3 k_{\text{obs}}$ versus [CTAB] in the oxidation reaction of 1-butanol with CTADC at 303 K.

[CTAB] against $\log k_{\text{obs}}$. The transition point experiences a maximum for butanol as the substrate revealing an increase in the critical concentration for reverse micellization (Figure 3). The sum over of group numbers as proposed by Davies²⁰ for calculating hydrophile–lipophile balance (HLB) values in the case of butanol is zero, suggesting almost no contribution toward micellization.

The alcohol chain length k_{obs} profile (Figure 4) experiences a plateau with an onset around hexanol. The trend in the rate may be ascribed to the partitioning of the substrate from the bulk to the interface. It gets support from the plot of $\log P$ (P being the partition coefficient of solvent distribution in the two-phase water–octanol system)²¹ against k_{obs} (Figure 5) which shows a similar trend.

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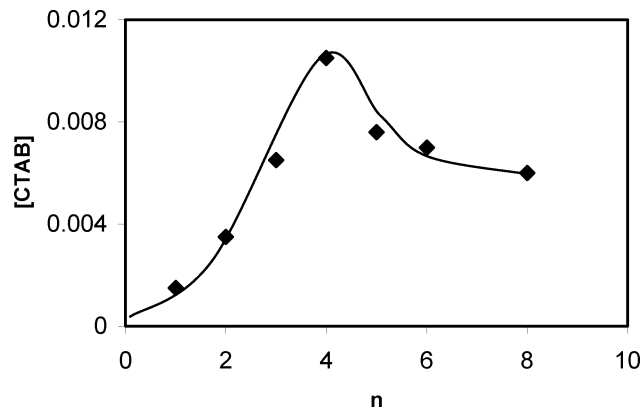


FIGURE 3. Plot of [CTAB] at the transition point versus n (no. of carbon atoms in the alcohol in a series of primary alcohols) in the oxidation reaction of alcohol with CTADC at 300 K.

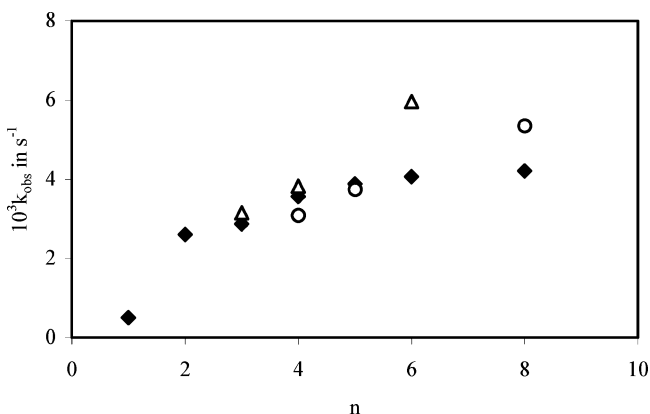


FIGURE 4. Plot of $10^3 k_{\text{obs}}$ versus n (no. of carbon atoms present in the alcohol) in the oxidation reaction of alcohols with CTADC at 303 K: \blacklozenge , n -alkyl; \circ , isoalkyl primary; \triangle , secondary alcohol.

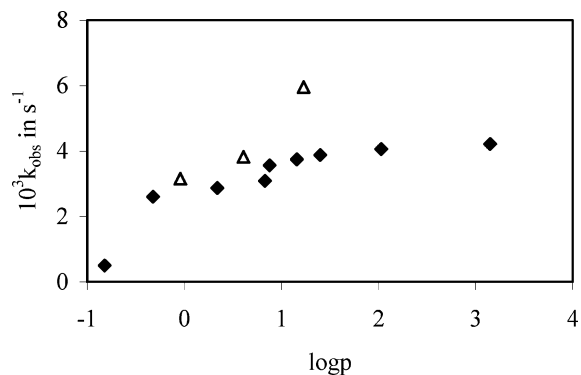


FIGURE 5. Plot of $10^3 k_{\text{obs}}$ versus $\log P$ (partition coefficient) in the oxidation reaction of alcohols with CTADC at 303 K: \blacklozenge , n -alkyl; \triangle , secondary alcohol.

The topological parameters are also good candidates to explain structure reactivity relationships for simple reaction centers. Randić²² has proposed a topological parameter, χ , involving connectivity of the methylene groups. The plot of χ against k_{obs} is shown in Figure 6. The k_{obs} values for normal chain alcohols are found to increase slowly until a plateau is observed. The onset of the plateau is found to be at butanol. An alcohol with a longer chain does not experience significant change because of elongation of the alkyl chain. For secondary alcohols, an increasing trend is observed, and cyclohexanol is

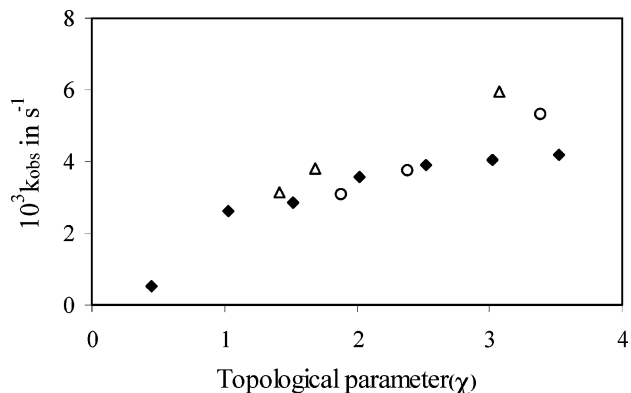


FIGURE 6. Plot of $10^3 k_{\text{obs}}$ versus χ (topological parameter) in the oxidation reaction of alcohols with CTADC at 303 K: \blacklozenge , n -alkyl; \circ , isoalkyl primary; \triangle , secondary alcohol.

found to have a positive deviation. In a micelle/reversed micelle, the hydroxy group is protruded in to the polar medium while the hydrophobic group remains embedded with the hydrophobic chain of the amphiphile. The protrusion of the hydroxy group depends on the HLB of the alcohol. Cyclohexanol with its structural artifact is more favorable for reverse micelle formation and thus more partitioned to the interface. The effective concentration of cyclohexanol thus increases at the interface.

The rate constants of thirteen different aliphatic alcohols were determined at three different temperatures, and the thermodynamic parameters such as ΔG^\ddagger , ΔH^\ddagger , and ΔS^\ddagger have been evaluated (Table 3). The ΔH^\ddagger values vary from 19.0 (for butanol) to 43.7 (for isobutyl alcohol) kJ mol^{-1} , and the ΔG^\ddagger values vary from 86.3 (for cyclohexanol) to 92.4 (methanol) kJ mol^{-1} . The ΔS^\ddagger values are found to span from -149 (for isobutyl alcohol) to -229 (for n -butanol) $\text{J mol}^{-1} \text{K}^{-1}$. The high negative values are indicative of a cyclic transition state. The constancy in ΔG^\ddagger values for all the substrates arises because a change in the ΔH^\ddagger and ΔS^\ddagger values indicates that all these reactions involve similar mechanistic pathway. The plot of ΔH^\ddagger and ΔS^\ddagger is found to be a straight line ($R^2 = 0.994$ excluding the values for methanol) with an isokinetic temperature of 308 K.

Solvent Effect. The mechanism of oxidation by CTADC stems from the following: (a) the partition factor i.e., the rate of depletion of the complex by a forward reaction (k_2) and by a backward reaction (k_{-1}); (b) stability of the transition state; (c) the partition of the oxidant and substrate in two micro-heterogeneous domains due to the formation of reversed micelle. To achieve a clear picture on these aspects, the reaction was investigated in a set of solvents with varied hydrophobicity and polarity, and the results are tabulated in Table 4. Effects of organic solvents on biological micro-heterogeneous reaction systems (as in protein assemblages) are accounted for both their direct influence on the hydrated shell and/or active center of the protein and the changes of electrostatic and hydrophobic intra- and intermolecular interactions.²³ In the present investigation we have used 15 organic solvents having nonpolar and dipolar aprotic characteristics. For the investigation of solvent effect, cyclohexanol is considered as the substrate because of its high reactivity. Further, as a secondary alcohol, it provides the proper geometry to contribute to the formation of a reversed micelle, where the surface area of the core/mesophase interfaces is less than the surface area of mesophase/bulk interface.

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TABLE 3. Observed Rate Constants and Activation Parameters of the Oxidation of Various Aliphatic Alcohols by CTADC in DCM^a

substrate	$10^3 k_{\text{obs}} \text{ s}^{-1}$			$\Delta H^\ddagger \text{ kJ mol}^{-1}$	$\Delta S^\ddagger \text{ J mol}^{-1} \text{ K}^{-1}$	$\Delta G^\ddagger \text{ kJ mol}^{-1}$
	298 K	303 K	308 K			
methanol	0.4	0.5	0.7	36.5	-188	92.4
ethanol	2.1	2.6	3.3	30.7	-193	88.3
1-propanol	2.4	2.9	3.5	26.8	-205	87.9
1-butanol	3.1	3.6	4.0	19.0	-229	87.3
1-pentanol	3.3	3.9	4.5	21.5	-220	87.2
1-hexanol	3.5	4.1	4.6	19.5	-226	87.0
1-octanol	3.5	4.2	5.1	27.0	-201	87.0
isobutyl alcohol	2.2	3.1	3.9	43.7	-149	88.2
isopentyl alcohol	2.9	3.7	4.7	32.9	-183	87.4
2-ethyl-1-hexanol	4.0	5.4	6.4	32.5	-182	86.6
2-propanol	2.4	3.2	4.1	39.0	-164	87.9
2-butanol	3.1	3.8	4.9	33.5	-181	87.3
Cyclohexanol	4.7	6.0	7.0	27.8	-196	86.3

^a [Substrate] = 0.5 M, [CTADC] = 1.89×10^{-4} M, and [acetic acid] = 3.24 M.

TABLE 4. Observed Rate Constants for the Oxidation Reaction of Cyclohexanol in Various Organic Solvents at 303 K^a

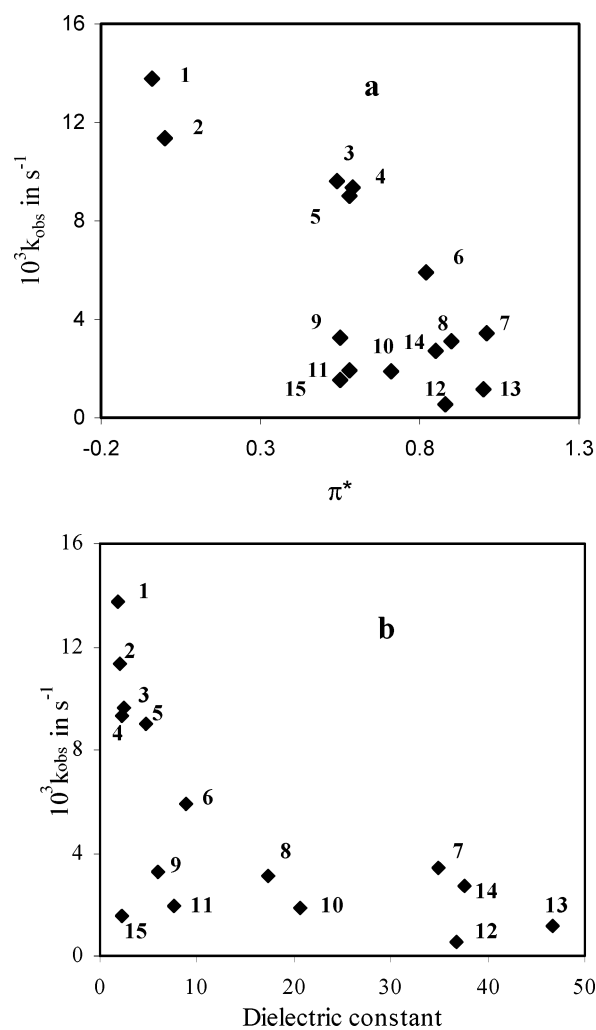
serial no.	solvent	$k_{\text{obs}} \times 10^3 \text{ s}^{-1}$
1	hexane	13.8
2	cyclohexane	11.4
3	toluene	9.6
4	benzene	9.4
5	chloroform	9.0
6	dichloromethane	5.9
7	nitrobenzene	3.4
8	acetophenone	3.1
9	ethyl acetate	3.3
10	acetone	1.9
11	tetrahydrofuran	1.9
12	<i>N,N</i> -dimethylformamide	0.6
13	dimethyl sulfoxide	1.2
14	acetonitrile	2.7
15	dioxane	1.5

^a [Cyclohexanol] = 0.5 M, [CTADC] = 1.89×10^{-4} M, and [acetic acid] = 3.24 M.

The plots of k_{obs} with various polarity parameters exhibit some interesting results. The analysis of the scattergram (Figure 7a) classifies the solvents into two sets, one set being due to toluene, benzene, chloroform, dichloromethane, and nitrobenzene ($k_{\text{obs}} = 0.0169 - 0.0132\pi^*$, $R^2 = 0.995$). When hexane and cyclohexane are included in this class, the correlation coefficient decreases to 0.8875 with a similar trend. For a set of solvents with acetone, acetonitrile, dioxane, tetrahydrofuran, nitrobenzene, and acetophenone, the rate increases with increasing polarity, and the relationship can be expressed as $k_{\text{obs}} = 0.004\pi^* - 0.0006$ ($R^2 = 0.9356$). DMF, DMSO, and ethyl acetate are found to be isolated. The former set is a nonpolar aprotic class of solvents but is found to exhibit a significant change in the reactivity because of a change in the polarity of the solvent. However, for the dipolar aprotic solvent of the latter class, no significant change is observed.

Similarly, the plot of dielectric constant values with k_{obs} (Figure 7b) is found to decrease asymptotically (excluding dioxane, ethyl acetate, and THF). There is a sharp decrease at a low dielectric constant (<10), while at higher values (10–50) the rate is virtually independent of the dielectric constant. This biphasic phenomenon suggests the differential contribution of the aforesaid factors to the reaction mechanism.

The plot of k_{obs} against a hydrogen-bond acceptor parameter, β ,²⁴ exhibits a negative slope with concavity indicating a significant decrease in the lower side of the β values (Figure

**FIGURE 7.** Plot of $10^3 k_{\text{obs}}$ versus (a) π^* (polarity parameter) and (b) ϵ (dielectric constant) in the oxidation reaction of cyclohexanol with CTADC at 303 K. The numeric values in the plot represent the serial number of solvents in Table 4.

8a). Thus the dipolar aprotic solvents also do not contribute to the reaction kinetics through the hydrogen bonding in the transition state. To examine the contribution of the solvent

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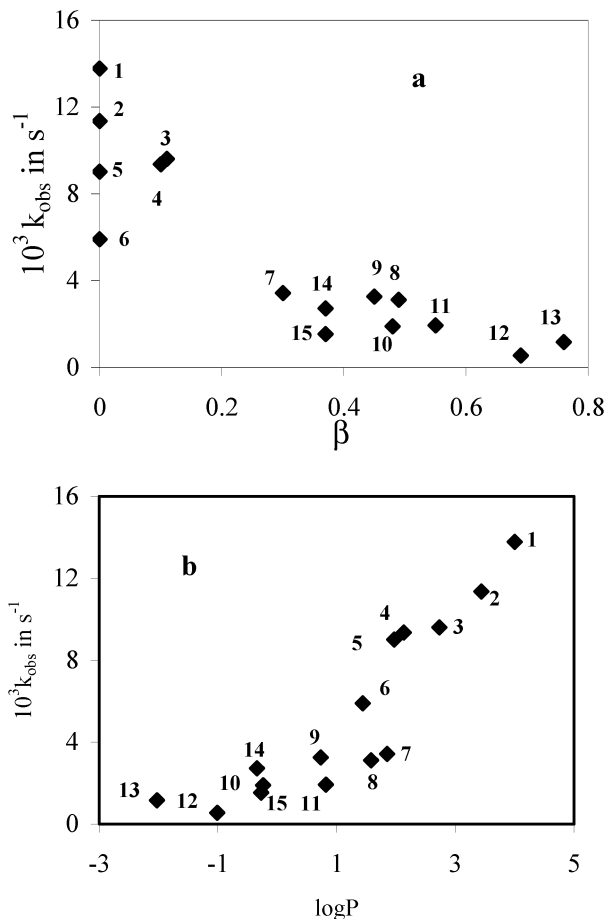


FIGURE 8. Plot of $10^3 k_{\text{obs}}$ versus (a) β (hydrogen-bond acceptor basicity) and (b) $\log P$ (partition coefficient) in the oxidation reaction of cyclohexanol with CTADC at 303 K.

through its hydrophobic characteristic, k_{obs} was correlated with $\log P$ values (Figure 8b).²⁵ The rate constant increases with increase in $\log P$ values, however, separating the solvents into two different classes. In a nonpolar aprotic solvent, the trend of increase is at the higher side ($k_{\text{obs}} = 0.0026 \log P + 0.003$, $R^2 = 0.980$), while in dipolar aprotic solvents the trend of increase is low ($k_{\text{obs}} = 0.0007 \log P + 0.0021$, $R^2 = 0.66$). The poor correlation obtained for dipolar aprotic solvents also corroborates the proposition that the polar characteristics do not contribute significantly to the reaction mechanism.

Further, to have a better insight on the contribution of electrostatic effect, if any, the rate constants were correlated with Swain's A and B parameters,²⁶ which explain the anion binding and cation binding capacity of the solvents, respectively. The plot of A with the k_{obs} is found to be bilinear (Figure 9a) with almost the same increasing and decreasing trends. The increasing trend is due to solvents such as chloroform, dichloromethane, nitrobenzene, acetone, and acetonitrile, and the decreasing trend is due to the other solvents. However, the plot of B with k_{obs} (Figure 9b) exhibits a negative slope indicating the involvement of a noncationic transition state.

From the above results it is apparent that the rate constants largely depend on the chemical nature of solvents. An increase

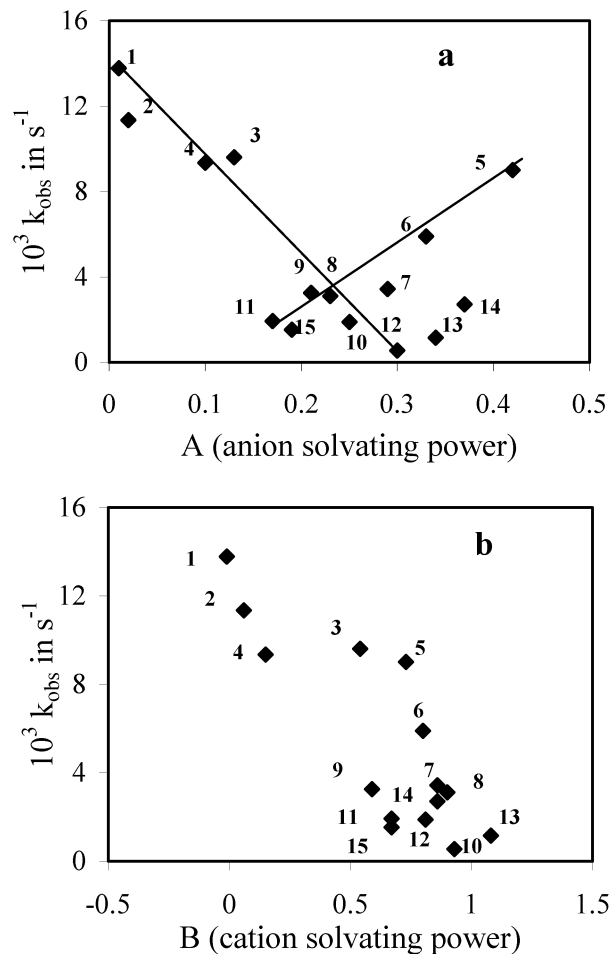


FIGURE 9. Plot of $10^3 k_{\text{obs}}$ versus (a) A (anion solvating power of the solvent) and (b) B (cation solvating power of the solvent) in the oxidation reaction of cyclohexanol with CTADC at 303 K.

in the dielectric constant at the higher side does not bring forth significant changes on the rate constant proposing least contribution of the electrostatic effect in the transition state. At the lower side of the dielectric constant, the sharp decrease may be attributed to the contribution of the solvent toward the formation of a reversed micelle, which controls the rate. The later proposition gets support from the linear relationship of the $\log P$ parameters with the rate constants. From the multiple regression of k_{obs} with $\log P$ and β (eq 4), it is clear that the hydrophobicity of the solvents has a positive contribution and the polarity of the solvents have a negative contribution toward the reaction, suggesting the existence of a relatively less polar (neutral) transition state than the reacting species

$$k_{\text{obs}} = [1.894 (\pm 0.328) \times 10^{-3}] \log P - [7.714 (\pm 2.091) \times 10^{-3}] \beta + 5.157 (\pm 0.982) \times 10^{-3} \quad (4)$$

($R = 0.975$, $F = 87.35$, $n = 12$ (excluding DMSO, DMF, nitrobenzene)).

Ionic surfactants, like quaternary ammonium salts, dissociate in aqueous medium and lead to a self-aggregation such as micellization, while in nonaqueous medium, quaternary ammonium salts exist as ion pairs or an aggregation of ion pairs.²⁷ The degree of aggregation of these salts or the phosphonium

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TABLE 5. Rate Constants, 10^4k_2 ($\text{dm}^3 \text{mol}^{-1} \text{s}^{-1}$), in Various Solvents for (a) Oxidation of Organic Sulfides by Pyridinium Fluorochromate,¹⁸ (b) Oxidation of Aliphatic Alcohols by Quinolinium Bromochromate,¹³ and (c) Oxidation of Aliphatic Aldehydes by 2,2'-Bipyridinium Chlorochromate²⁹

solvent	10^3k_2 $\text{dm}^3 \text{mol}^{-1} \text{s}^{-1}$		
	a	b	c
cyclohexane	10.0	0.0129	0.062
toluene	79.3	0.123	0.537
benzene	318	0.148	0.676
chloroform	527	0.447	1.55
dichloromethane	565	0.479	1.74
dimethyl sulfoxide	1630	1.68	5.62
acetone	314	0.437	1.82
<i>N,N</i> -dimethyl formamide	730	0.891	2.82
tetrahydrofuran	186	0.2	0.955
ethyl acetate	130	0.162	0.692
1,4-dioxan	200	0.229	0.851
nitrobenzene	636	0.575	2.04
acetophenone	485	0.813	2.34
1,2-dichloroethane	444	0.55	1.96
butanone	250	0.302	1.35
acetic acid	253	0.0724	0.214
<i>t</i> -butyl alcohol	223	0.178	0.631
1,2-dimethoxy ethane	147	0.11	0.479
carbon disulfide	40.1	0.0513	0.245

analogues in a nonpolar solvent is inversely proportional to the polarity of the medium.²⁸ Lee and Brown, while investigating the oxidation kinetics of some organic substrates by using symmetrical and nonsymmetrical quaternary ammonium permanganates in organic solvents, have proposed that the rate of reaction is faster in the case of nonsymmetrical quaternary ammonium ions, where the interionic distance is less compared to symmetrical counterparts. Further, the nature of quaternary ammonium ions does not contribute to the change in reactivity in a polar solvent, while in nonpolar solvents a significant variation in rate constants is observed.^{8a} The above results clearly support our proposal that the nonsymmetrical quaternary ammonium ion, CTA^+ , with a counterion like dichromate can form a tight ion pair in nonpolar solvents and can aggregate to influence the reactivity of CTADC.

To compare the effect of the structure of a quaternary ammonium ion on the solvent effect in Cr(VI) oxidation, the work on the oxidation of various organic substrates with different Cr(VI) oxidants having counterions such as pyridinium or quinolinium have been collected from literature and given in Table 5. These reagents provide a homogeneous reaction medium, and there is no report of self-aggregation of these reagents. The plots of the rate data of any two reaction-systems with varying solvents are found to be linear with no deviation, proposing almost similar effect of the solvents on the transition state of the reactions. However, when our data were plotted against the rate data as mentioned in Table 3, scattergrams are obtained suggesting differences either in reaction mechanism or in the local environment of the reaction intermediate. The mechanism of the reaction being almost similar, the deviation

from linearity may be ascribed to a change in the reaction system, maybe because of self-aggregation of CTADC.

The rate constants of the oxidation of cholesterol⁶ and alkyl alcohols in the present study in various solvents by CTADC were plotted against each other. The plot is found to exhibit an increasing trend initially and then levels off for certain solvents indicating that there is a significant change in the behavior of solvents to the mechanism. Cholesterol, capable of forming self-aggregates, does not suffer much change in the solvent of high polarity when compared to aliphatic alcohols.

The relationship of the rate constants of the reaction of cyclohexanol with the solvent parameters thus envisages that the reaction involves a noncationic transition state that is relatively less polar than the reacting species, and CTADC appears to form self-aggregation and controls the reaction.

Experimental Section

Materials. Cetyltrimethylammonium dichromate (CTADC) was prepared by the method reported earlier,¹² and its purity was checked by estimating Cr(VI) iodometrically.³⁰ Alcohols were obtained in analytical grade and distilled before use. Glacial acetic acid was used without further purification. The organic solvents were purified by the standard methods.³¹ The surfactant cetyltrimethylammonium bromide (CTAB) was purified by recrystallization from methanol solution, and its purity was checked by measuring the conductance in aqueous medium. The deuterio samples (D_2O and CD_3OD) are of NMR grade with 99.8% D and were used as such.

Kinetic Measurements. The oxidation kinetics of alcohols by CTADC in the presence of acetic acid were investigated in different solvents and surfactant systems as reported earlier.⁶ The solvent isotope effect was investigated using 1:1 mixtures of H_2O /acetic acid and D_2O /acetic acid instead of DCM during kinetics studies. Acetic acid was equilibrated with H_2O and D_2O separately for 3 h before its use in the reaction process.

Product Analysis. After keeping the reaction mixture of CTADC, alcohols, and acetic acid in proper composition for 12 h in DCM, the volume of the reaction mixture was reduced to 20% under vacuum. The mixture was eluted in a silica column with a mixture of hexane and ethyl acetate as the eluent. The aldehyde and ketones were separated from the mixtures with other products. For the characterization of the products, the corresponding phenylhydrazones were prepared by the treatment of 2,4-dinitrophenylhydrazine reagent with the product formed, and the melting points were found to agree well with those of authentic samples.

Stoichiometry. The stoichiometry of the reaction was determined by performing the experiment at 303 K, under the condition of $[\text{CTADC}] \approx [\text{cyclohexanol}]$ at varying cyclohexanol concentrations. The disappearance of Cr(VI) was followed, until the absorbance values become constant. The $[\text{CTADC}]$ was estimated after 48 h. A stoichiometry ratio, $\Delta[\text{CTADC}]/\Delta[\text{cyclohexanol}] \approx 0.33$ was observed, which confirmed a 1:3 CTADC/cyclohexanol relationship.

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