Osmium(VIII) Catalysed Oxidation of Diclofenac Sodium by Diperiodato-argentate(III) Complex in Aqueous Alkaline Medium

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Abstract: The kinetics of Osmium(VIII) (Os(VIII)) catalysed oxidation of diclofenac sodium (DFS) by diperiodatoargentate(III) (DPA) in alkaline medium at a constant ionic strength of 0.60 mol dm^{-3} has been studied spectrophotometrically. The stoichiometry was found to be 1:1 i.e, one mole of DFS reacted with one mole of DPA. The reaction was first order with respect to [DPA] and [Os(VIII)], less than unit order in both [DFS] and [alkali] and negative fractional order in [periodate]. The effect of added products, ionic strength and dielectric constant of the medium was studied. The oxidation reaction in alkaline medium has been shown to proceed *via* a Os(VIII)-DFS complex, which further reacts with one molecule of monoperiodatoargentate in a rate determining step followed by other fast steps to give the products. The oxidation products were identified by LC-ESI-MS, NMR and IR spectral studies. The reaction constants involved in different steps of the mechanism were calculated. The activation parameters with respect to slow step of the mechanism were computed and discussed and thermodynamic quantities were also determined. The catalytic constant (K_c) was also calculated for Os(VIII) catalysis at different temperatures and values of activation parameters with respect to the catalyst have been evaluated. The active species of catalyst and oxidant have been identified.

Keywords: Kinetics, oxidation, diclofenac sodium, diperiodatoargentate(III), Os(VIII) catalysis.

1. INTRODUCTION

Diperiodatoargentate(III) (DPA) is a powerful oxidising agent in alkaline medium with reduction potential [1] 1.74 V. It is widely used as a volumetric reagent for the determination of various organic and inorganic species [2]. Jayaprakash Rao *et al.* [3] have used DPA as an oxidising agent for the kinetics of oxidation of various organic substrates. They normally found that order with respect to both oxidant and substrate was unity and [OH⁻] was found to enhance the rate of reaction. It was also observed that they did not arrive the possible active species of DPA in alkali and on the other hand they proposed mechanisms by generalising the DPA as $[Ag(HL)L]^{(x+1)-}$. However, Kumar *et al.* [4] put an effort to give an evidence for the reactive form of DPA in the large scale of alkaline pH. In the present investigation, we have obtained the evidence for the reactive species for DPA in alkaline medium.

Diclofenac, [o-(2,6-dichlorophenyl)amino]phenyl] acetic acid (DFS) belongs to a class of drugs called nonsteroidal anti-inflammatory drugs (NSAIDs). In pharmacological studies, diclofenac has shown anti-inflammatory, analgesic and antipyretic activity [5]. As with other NSAIDs, its mode of action is not known; its ability to inhibit prostaglandin synthesis, however, may be involved in its anti-inflammatory activity, as well as contributing to its efficiency in relieving pain related to inflammation and primary dysmenorrhea. Diclofenac is used in treating osteoarthritis, rheumatoid arthritis and ankylosing spondylitis [6]. Due to its low solubility, it is commercially available as its sodium salt.

In recent years, the use of transition metal ions such as osmium, ruthenium and iridium, either alone or as binary mixtures, as catalysts in various redox processes has attracted considerable interest [7]. The role of osmium(VIII) as a catalyst in some redox reactions has been reviewed [8]. Although the mechanism of catalysis depends on the nature of the substrate, the oxidant and experimental conditions, it has been shown [9] that metal ions act as catalysts by one of these different paths such as the formation of complexes with reactants or oxidation of the substrate itself or through the formation of free radicals.

Osmium(VIII) catalysis in redox reactions involves different degrees of complexity, due to the formation of different intermediate complexes and different oxidation states of osmium. The uncatalysed reaction of oxidation of DFS by DPA has been studied [10]. We have observed that osmium(VIII) catalyses the oxidation of DFS by DPA in alkaline medium in micro amounts.

So far there is no report on the kinetics of Os(VIII) catalysed oxidation of DFS by DPA**.** In view of potential pharmaceutical importance of DFS, the active species of Ag(III), osmium(VIII) and the complexity of the reaction, a detailed study of the reaction becomes important. The present investigation is aimed at checking the reactivity of DFS towards DPA in osmium(VIII) catalysed reaction and to understand the active species of oxidant and catalyst. Further we have isolated the oxidized products in a way to arrive at a suitable mechanism on the basis of kinetic and spectral results and to compute the thermodynamic quantities of various steps. An understanding of the mechanism allows the chemistry to be interpreted, understood and predicted.

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2. EXPERIMENTAL

2.1. Materials and Reagents

All reagents were of reagent grade and millipore water was used throughout the work. A solution of DFS (IP) was prepared by dissolving an appropriate amount of recrystallised sample in millipore water. The purity of DFS concentration was checked by potentiometrically. The IR spectrum of DFS agreed with that of literature. The required concentration of DFS was used from its stock solution. A standard stock solution of Os(VIII) was prepared by dissolving OsO_4 oxide (Johnson Matthey) in 0.50 mol dm^{-3} NaOH. The concentration was ascertained [11] by determining the unreacted $[Fe(CN)_6]^{4-}$ with standard Ce(IV) solution in an acidic medium. The ionic strength and alkalinity of the reaction were maintained by KNO_3 and KOH (BDH) respectively. An aqueous solution of $AgNO_3$ was used to study the product effect, Ag(I). A stock solution of IO_4^- was prepared by dissolving a known weight of KIO_4 (Riedel-de-Haen) in hot water and used after keeping for 24h. Its concentration was ascertained iodometrically [12], at neutral pH maintained using phosphate buffer.

2.2. Preparation of DPA

DPA was prepared by oxidising Ag(I) in presence of KIO_4 as described elsewhere [13]. The complex was characterized from its UV spectrum, which exhibited three peaks at 216, 255 and 362 nm. These spectral features were identical to those reported earlier for DPA [13]. The magnetic moment study revealed that the complex is diamagnetic. The compound prepared was analysed [14] for silver and periodate by acidifying a solution of the material with HCl, recovering and weighing the AgCl for Ag and titrating the iodine liberated when excess KI was added to the filtrate for IO_4^-. The aqueous solution of DPA was used for the required [DPA] in the reaction mixture.

2.3. Instruments Used

A)   For kinetics measurements, CARY 50 Bio UV–vis Spectrophotometer (Varian, Victoria-3170, Australia) was used.

B)   For product analysis, an LC-ESI-MS (Hewlett-Packard GmbH, Waldbronn, Germany), Nicolet 5700 – FT-IR spectrometer (Thermo, U.S.A.) and 300 MHz ^{1}H NMR spectrometer (Bruker, Switzerland) were used.

C)   The pH of the medium in the solution was measured by [ELICO (L1613)] pH meter.

2.4. Kinetic Measurements

The kinetics of Os(VIII) catalysed oxidation of DFS by DPA was followed under pseudo first order condition where [DFS] > [DPA] catalysed reaction at 298 K, unless specified. The reaction in the presence of catalyst was initiated by mixing DFS to DPA solution which also contained the required concentration of KNO_3, KOH, Os(VIII) catalyst and KIO_4. The progress of the reaction was monitored spectrophotometrically at 360nm (i.e., decrease in absorbance due to DPA with the molar absorbancy index, 'ε' to be 13,900 $\pm$ 100 dm^3 mol^{-1} cm^{-1}), which is the maximum absorption wavelength of DPA. The spectral changes during

the reaction infer that the concentration of DPA decreases at 360nm. It was verified that there was almost no interference from other species in the reaction mixture at this wavelength.

The pseudo-first order rate constants, 'k_c' were determined from the log (absorbance) *vs* time plots. The plots were linear up to 80% completion of reaction under the range of [OH^-] used. The orders for various species were determined from the slopes of plots of log k_c *vs* respective concentration of species except for [DPA] in which non-variation of 'k_c' was observed as expected to the reaction condition. During the kinetics a constant concentration, viz. 1.0 x 10^{-5} mol dm^{-3} of KIO_4 was used throughout the study unless otherwise stated. Since periodate is present in the excess in DPA, the possibility of oxidation of DFS by periodate in alkaline medium at 298 K was tested. The progress of the reaction was followed iodometrically. However, it was found that there was no significant reaction under the experimental conditions employed compared to the DPA oxidation of DFS. The total concentrations of periodate and alkali was calculated by considering the amount present in the DPA solution and that additionally added. Dissolved O_2, CO_2 and surface of reaction vessel had no effect on the reaction rate. Fresh solutions were used for carrying out each kinetic study.

3. RESULTS

3.1. Stoichiometry and Product Analysis

Different sets of reaction mixtures containing varying ratios of DPA to DFS in presence of constant amount of OH^-, KIO_4, KNO_3, and Os(VIII) were kept for 4 hrs in a closed vessel under nitrogen atmosphere. The remaining concentration of DPA was assayed by measuring the absorbance at 360nm. The results indicated that   one mole of DFS reacted with one mole of DPA, as given in Scheme **1**.

The oxidation product of DFS, [2-(2, 6-dichloro-phenylamino)-phenyl]-methanol was isolated with the help of preparative TLC and other separation technique and characterized by LC-ESI-MS, FTIR and ^{1}H-NMR spectral studies.

LC-ESI-MS analysis was carried out using reverse phase high performance liquid chromatography (HPLC) system with a phenomenon C-18 column, UV/Visible detector and series mass analyzer. 12 µL of acidified reaction mixture was injected. The mobile phase consisted of 10 mM ammonium acetate pH 3.0(eluent A) and acetic acid(eluent B) at a flow rate of 1 ml/min. Gradient elution was run to separate the substrate and reaction products. LC-ESI-MS analysis indicated the presence of two main products with molecular ions of m/z at 273(Yield ca 90%) and 598(Yield ca 5%) respectively (Fig. **1**). The molecular ion of DFS is m/z 299. The m/z at 598 corresponds to dimer product of DFS. The product [2-(2, 6-dichloro-phenylamino)-phenyl]-methanol is further confirmed by its characteristic IR and ^{1}H NMR spectrum. The disappearance of the sharp band (peak) at 1695 cm^{-1} due to acidic carbonyl in DFS confirms the product. Further secondary amine (-NH) group observed around 3387cm^{-1} in DFS, remains in the product (Fig. **2**). In ^{1}H-NMR (DMSO) spectrum shows, the disappearance of the acidic -OH band of DFS and appearance of alcoholic

hydroxyl proton triplet band at 6.859ppm confirms the product. Further secondary amine(-NH) proton singlet band around 3.69ppm and other aromatic proton bands in DFS remains in the product, which disappears on D_2O exchange confirms the formation of product [2-(2, 6-dichloro-phenylamino)-phenyl]-methanol (Fig. **3**). All these observations proved the formation of [2-(2, 6-dichloro-phenylamino)-phenyl]-methanol as a major product. The formation of free Ag^+ in solution was detected by adding KCl solution to the reaction mixture, which produced white turbidity due to the formation of AgCl. The dimer structure of DFS is
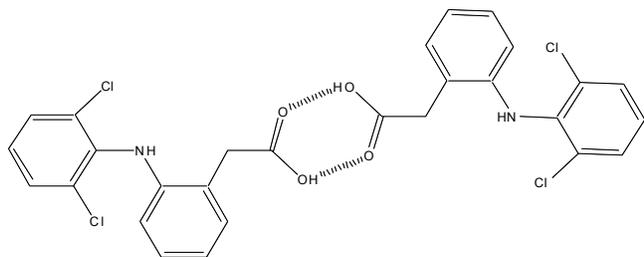
Regression analysis of experimental data to obtain the regression coefficient r and standard deviation S, of points from the regression line was performed using Microsoft Excel-2003 programme.

3.2. Reaction Orders

As the diperiodatoargentate(III) oxidation of DFS in alkaline medium proceeds with a measurable rate in the absence of Os(VIII), the catalysed reaction is understood to occur in parallel paths with contributions from both the catalysed and uncatalysed paths. Thus the total rate constant (k_T) is equal to the sum of the rate constants of the catalysed (k_C) and uncatalysed (k_U) reactions, so $k_C = k_T - k_U$. Hence the reaction orders have been determined from the slopes of log k_C versus log(concentration) plots by varying the concentrations of DFS, IO_4^-, OH^- and Os(VIII), in turn while keeping others constant. The DPA concentration was varied in the range of 1.0×10^{-5} to 1.0×10^{-4} mol dm^{-3} and the linearity of the plots of log(absorbance) *vs* time up to 80% completion of reaction indicates a reaction order unity in [DPA] (Fig. **4**). This is also confirmed by varying of [DPA], which did not result in any change in the pseudo first-order rate constants, k_C (Table **1**). The substrate DFS was varied in the range of 1.0×10^{-4} to 1.0×10^{-3} mol dm^{-3} at 298 K while keeping other reactant concentration and condition constant. The k_C values increased with increase in concentration of DFS indicating an apparent less than unit order dependence on [DFS] (Table **1**). The effect of alkali on the reaction has been studied in the range of 0.05 to 0.50 mol dm^{-3} at constant concentrations of DFS, DPA, Os(VIII), IO_4^- and a constant
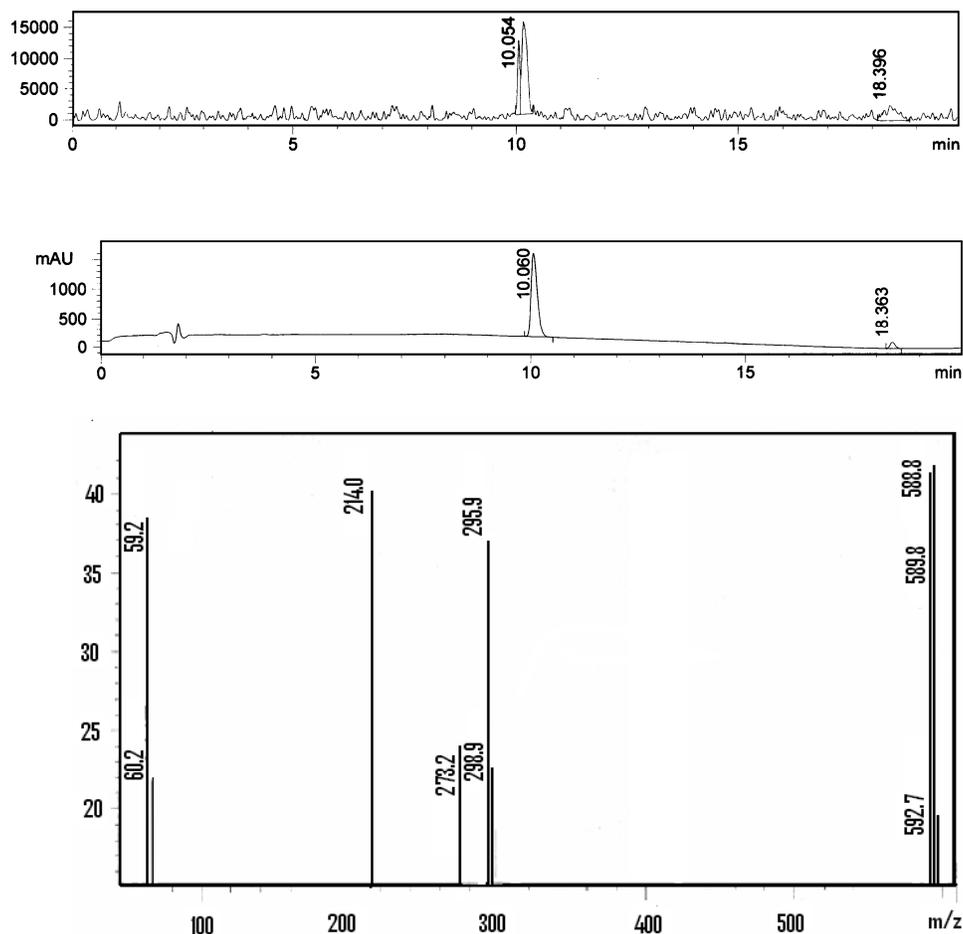

Fig. (1). Chromatogram & LC - ESI - MS spectra of the product of Os(VIII) catalysed oxidation of diclofenac sodium by diperiodatoargantate (III) in aqueous alkaline medium.
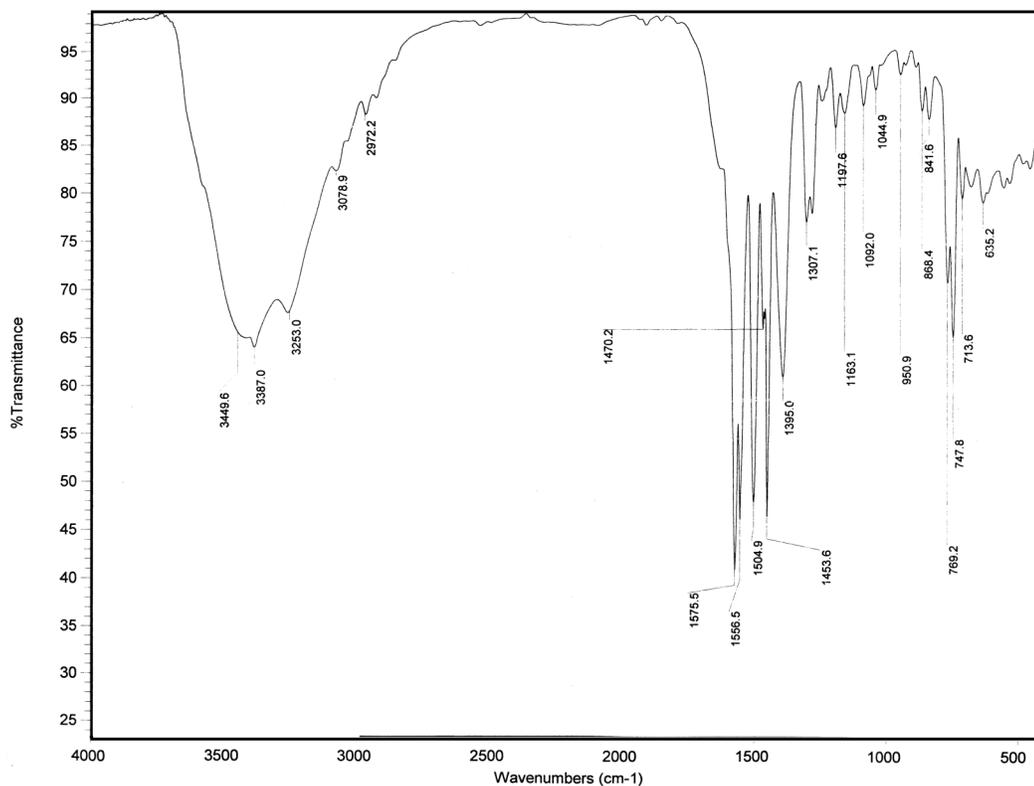
Fig. (2). FT-IR spectra of the product of Os(VIII) catalysed of oxidation of diclofenac sodium by diperiodatoargantate (III) in aqueous alkaline medium.
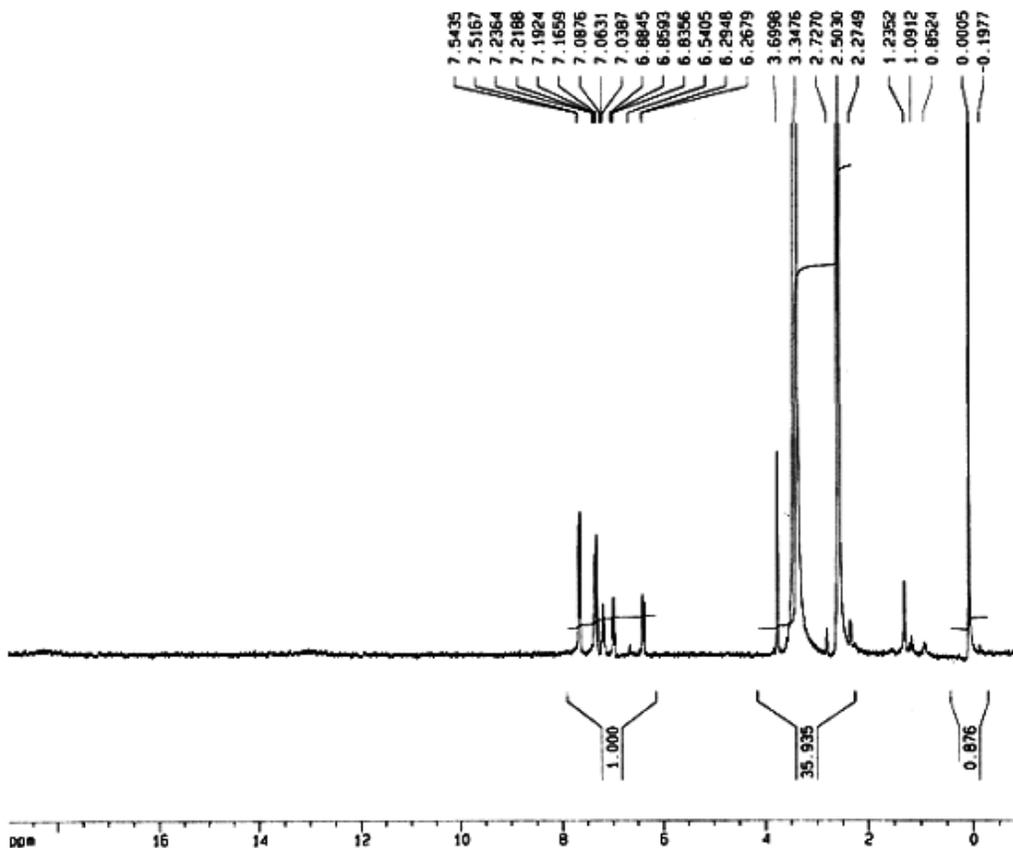
Fig. (3). ^{1}H-NMR spectra of the product of Os(VIII) catalysed oxidation of diclofenac sodium by diperiodatoargantate (III)in aqueous alkaline medium.

COO$^-$ + $[Ag(H_2IO_6)(H_2O)_2]$ $\xrightarrow{Os(VIII)}$ CH$_2$OH

+ HCO$_3^-$ + Ag(I) + H$_2$IO$_6^{3-}$ + 2H$^+$

Scheme 1. 1:1 stoichiometry.

$[Ag(H_3IO_6)_2]^-$ + OH$^-$ $\xrightleftharpoons{K_1}$ $[Ag(H_2IO_6)(H_1IO_6)]^{2-}$ + H$_2$O

$[Ag(H_2IO_6)(H_3IO_6)]^{2-}$ + 2H$_2$O $\xrightleftharpoons{K_2}$ $[Ag(H_2IO_6)(H_2O)_2]$ + $[H_3IO_6]^{2-}$

COO$^-$ + $[OsO_4(OH)_2]^{2-}$ $\xrightleftharpoons{K_3}$ Complex (C)

Complex (C) + $[Ag(H_2IO_6)(H_2O)_2]$ $\xrightarrow[slow]{k}$ $\dot{C}H_2$ + $[Ag(OH)]^+$ + HCO$_3^-$

+ H$_2$IO$_6^{3-}$ + 2H$^+$ + $[OsO_4(OH)_2]^{2-}$

$\dot{C}H_2$ + $[Ag(OH)]^+$ $\xrightarrow{fast}$ CH$_2$OH + Ag(I)

Scheme 2. Detailed Scheme for the oxidation of osmium(VIII) catalysed oxidation of DFS by diperiodatoargentate(III) in aqueous alkaline medium.

Scheme 3. The probable structure of the osmium(VIII) and DFS complex.

Fig. (4). First order plots on the Os(VIII) catalysed oxidation of diclofenac sodium by diperiodatoargantate (III) in aqueous alkaline medium at 25^{0}C. [DPA] x10^5 mol dm^{-3}:1)1.0 2)3.0 3) 5.0 4) 8.0 5) 10.0.

Table 1.   Effect of Variation of [DPA], [DFS], [OH⁻], [IO₄⁻] and [Os(VIII)] on the Osmium(VIII) Catalysed Oxidation of DFS by DPA in Aqueous Alkaline Medium at 298 K and I = 0.60 mol dm⁻³

$[DPA] \times 10^5$ (mol dm⁻³)	$[DFS] \times 10^4$ (mol dm⁻³)	$[OH^-]$ (mol dm⁻³)	$[IO_4^-] \times 10^5$ (mol dm⁻³)	$[Os(VIII)] \times 10^6$ (mol dm⁻³)	$k_T \times 10^3$ (s⁻¹)	$k_U \times 10^4$ (s⁻¹)	$k_C \times 10^3$ (s⁻¹)	
							Found	**Calculated**
1.0	5.0	0.5	1.0	8.0	2.36	7.30	1.63	1.63
3.0	5.0	0.5	1.0	8.0	2.35	7.16	1.63	1.63
5.0	5.0	0.5	1.0	8.0	2.34	7.38	1.60	1.63
8.0	5.0	0.5	1.0	8.0	2.35	7.14	1.64	1.63
10.0	5.0	0.5	1.0	8.0	2.33	7.20	1.61	1.63
5.0	1.0	0.5	1.0	8.0	0.69	2.21	0.47	0.47
5.0	3.0	0.5	1.0	8.0	1.63	5.30	1.10	1.16
5.0	5.0	0.5	1.0	8.0	2.42	7.38	1.68	1.63
5.0	8.0	0.5	1.0	8.0	2.95	8.81	2.07	2.12
5.0	10.0	0.5	1.0	8.0	3.40	9.80	2.42	2.35
5.0	5.0	0.05	1.0	8.0	0.64	1.88	0.45	0.45
5.0	5.0	0.08	1.0	8.0	0.91	2.56	0.65	0.65
5.0	5.0	0.1	1.0	8.0	1.08	3.21	0.76	0.76
5.0	5.0	0.3	1.0	8.0	1.92	6.07	1.31	1.37
5.0	5.0	0.5	1.0	8.0	2.42	7.38	1.68	1.63
5.0	5.0	0.5	1.0	8.0	2.42	7.38	1.68	1.63
5.0	5.0	0.5	3.0	8.0	1.45	4.25	1.02	1.00
5.0	5.0	0.5	5.0	8.0	1.02	2.99	0.72	0.72
5.0	5.0	0.5	8.0	8.0	0.72	2.06	0.51	0.51
5.0	5.0	0.5	10.0	8.0	0.61	1.71	0.44	0.42
5.0	5.0	0.5	1.0	4.0	1.54	7.38	0.80	0.81
5.0	5.0	0.5	1.0	8.0	2.40	7.38	1.66	1.63
5.0	5.0	0.5	1.0	10.0	2.83	7.38	2.09	2.04
5.0	5.0	0.5	1.0	20.0	4.98	7.38	4.24	4.08
5.0	5.0	0.5	1.0	40.0	9.28	7.38	8.54	8.16

ionic strength of 0.60 mol dm⁻³. The rate constants increased with increasing [alkali] and the order was found to be less than unity (Table **1**).

3.3. Effect of [Periodate]

Periodate concentration was varied from 1.0×10^{-5} to 1.0×10^{-4} mol dm⁻³ at constant [DPA], [DFS], [Os(VIII)] and ionic strength. It was observed that the rate constants decreased by increasing [IO₄⁻] (Table **1**).

3.4. Effect of Added Products

The effect of initially added products, [2-(2,6-dichlorophenylamino)-phenyl]-methanol and Ag(I) (AgNO₃) did not have any significant effect on the rate of the reaction.

3.5. Effect of Ionic Strength and Dielectric Constant

The ionic strength (addition of KNO₃) and dielectric constant(t-butyl alcohol-water %) of the medium had no significant effect on the rate of reaction.

3.6. Test for Free Radicals (Polymerization Study)

The intervention of free radicals in the reaction was examined as follows. The reaction mixture, to which a known quantity of acrylonitrile monomer was initially added, was kept for 2 hrs in an inert atmosphere. On diluting the reaction mixture with methanol, white precipitate was formed, indicating the intervention of free radicals in the

reaction. The blank experiments of either DPA or DFS alone with acrylonitrile did not induce any polymerization under the same condition as those induced for reaction mixture. Initially added acrylonitrile decreases the rate of reaction indicating free radical intervention, which is the case in earlier work [15].

3.7. Effect of Temperature (T)

The influence of temperature on the rate of reaction was studied at 293, 298, 303 and 313 K. The rate constants (k), of the slow step of Scheme **2** were obtained from the slopes and the intercepts of the plots of [Os(VIII)]/k_C *vs* 1/[DFS] plot at four different temperatures. The values are given in Table **2**. The activation parameters for the rate determining step were obtained by the least square method of plot of log k versus 1/T and are presented in Table **2**.

3.8. Effect of [Os(VIII)]

The [Os(VIII)] concentrations was varied from 4.0×10^{-6} to 4.0×10^{-5} mol dm⁻³ range, at constant concentration of DPA, DFS, alkali and ionic strength. The order in [Os(VIII)] was found to be unity.

3.9. Catalytic Activity

It has been pointed out by Moelwyn-Hughes [16] that in the presence of catalyst, the uncatalysed and catalysed reactions proceed simultaneously, so that,

$$k_T = k_U + K_C[\text{catalyst}]^x \qquad (1)$$

Table 2. Activation Parameters and Thermodynamic Quantities for the Osmium(VIII) Catalysed Oxidation of DFS by DPA in Aqueous Alkaline Medium with Respect to the Slow Step of Scheme 2

(a) Effect of Temperature

Temperature (K)	$k \times 10^{-2}$ ($dm^3 \, mol^{-1} \, s^{-1}$)
293	4.19
298	5.28
303	6.36
313	8.51

(b) Activation Parameters

Parameter	Value
E_a ($kJ \, mol^{-1}$)	26.7 ± 1.2
$\Delta H^{\#}$ ($kJ \, mol^{-1}$)	24.2 ± 1.2
$\Delta S^{\#}$ ($JK^{-1} \, mol^{-1}$)	-111 ± 5
$\Delta G^{\#}$ ($kJ \, mol^{-1}$)	57.4 ± 2.8
log A	7.4 ± 0.3

(c) Effect of Temperature on K_1, K_2 and K_3 for the Osmium(VIII) Catalysed Oxidation of DFS by DPA in Aqueous Alkaline Medium

Temperature (K)	K_1 ($dm^3 \, mol^{-1}$)	$K_2 \times 10^4$ ($mol \, dm^{-3}$)	$K_3 \times 10^{-3}$ ($dm^3 \, mol^{-1}$)
293	0.13 ± 0.006	1.67 ± 0.08	1.88 ± 0.09
298	0.20 ± 0.008	1.03 ± 0.05	2.60 ± 0.12
303	0.27 ± 0.01	0.61 ± 0.03	3.23 ± 0.16
313	0.50 ± 0.02	0.24 ± 0.01	6.63 ± 0.32

(d) Thermodynamic Quantities Using K_1, K_2 and K_3

Thermodynamic Quantities	Values from K_1	Values from K_2	Values from K_3
ΔH ($kJ \, mol^{-1}$)	50.5 ± 2.5	-73.8 ± 3.6	47.6 ± 2.3
ΔS ($JK^{-1} \, mol^{-1}$)	156 ± 7	-324 ± 16	225 ± 11
ΔG ($kJ \, mol^{-1}$)	3.5 ± 0.1	24.0 ± 1.1	-19.7 ± 0.9

Here k_T is the observed pseudo first-order rate constant in the presence of Os(VIII) catalyst ; k_U, the pseudo first-order rate constant for the uncatalysed; K_C, the catalytic constant and 'x' the order of the reaction with respect to Os(VIII). In the present investigations; x values for the standard run were found to be unity for Os(VIII). Then the value of K_C is calculated using the equation,

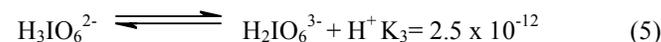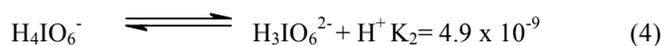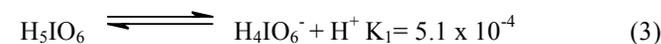$$K_C = \frac{k_T - k_U}{[\text{Os(VIII)}]} = \frac{k_C}{[\text{Os(VIII)}]}$$

$$(\text{where, } k_T - k_U = k_C) \qquad (2)$$

The values of $K_C \times 10^{-2}$ were obtained as 1.4, 2.1, 2.5 and 4.6 at 293, 298, 303 and 313 K temperatures respectively. Further, plots of log K_C *vs* 1/T were linear and the values of energy of activation and other activation parameters with reference to catalyst were computed as Ea ($kJ \, mol^{-1}$) = 43.6, $\Delta H^{\#}$ ($kJ \, mol^{-1}$) = 41.1, $\Delta S^{\#}$ ($JK^{-1} mol^{-1}$) = -62.3, $\Delta G^{\#}$ = 59.7 and log A = 9.96.

4. DISCUSSION

The powerful and versatile nature of two electron-oxidant Ag(III) has led to its use for oxidation of various organic and inorganic substrates. $Ag(OH)_4^-$, diperiodatoargentate(III) and ethylenebis (biguanide), (EBS), silver(III) are among those Ag(III) species which have drawn maximum attention due to their relative stability [17]. The stability of $Ag(OH)_4^-$ is very sensitive towards traces of dissolved oxygen and other impurities in the reaction medium, therefore it had not drawn much attention. However, the other two forms of Ag(III) [3,4,18] are considerably more stable; DPA is used in highly alkaline medium and EBS is used in highly acidic medium.

A literature survey [13] reveals that the water soluble diperiodatoargentate(III) (DPA) has a formula $[Ag(IO_6)_2]^{7-}$ with dsp^2 configuration of square planar structure, similar to a diperiodatocopper(III) complex with two bidentate ligands, periodate to form a planar molecule. When the same molecule is used in alkaline medium, it is unlikely to exist as $[Ag(IO_6)_2]^{7-}$ as a periodate is known to be in various protonated forms [19, 20] depending on the pH of the solution as given in following multiple equilibria (3)-(5).

$$H_5IO_6 \rightleftharpoons H_4IO_6^- + H^+ \quad K_1 = 5.1 \times 10^{-4} \qquad (3)$$

$$H_4IO_6^- \rightleftharpoons H_3IO_6^{2-} + H^+ \quad K_2 = 4.9 \times 10^{-9} \qquad (4)$$

$$H_3IO_6^{2-} \rightleftharpoons H_2IO_6^{3-} + H^+ \quad K_3 = 2.5 \times 10^{-12} \qquad (5)$$

Periodic acid (H_5IO_6) exists in acid medium and also as $H_4IO_6^-$ at pH 7. Thus, under the present alkaline conditions, the main species are expected to be $H_3IO_6^{2-}$ and $H_2IO_6^{3-}$. At higher concentrations, periodate also tends to dimerise [1]. On the contrary, in the literature [3] proposed the DPA as $[Ag(HL)_2]^{x-}$ in which "L" is a periodate with an uncertain number of protons and "HL" is a protonated periodate of uncertain number of protons. This can be ruled out by considering the alternative form [19,20] of IO_4^- at pH > 7 which is in the form $H_3IO_6^{2-}$ or $H_2IO_6^{3-}$. Hence, DPA could exist as $[Ag(H_3IO_6)_2]^-$ or $[Ag(H_2IO_6)_2]^{3-}$ in alkaline medium. Therefore, under the present condition, diperiodatoargentate(III), may be depicted as $[Ag(H_3IO_6)_2]^-$. The similar speciation of periodate in alkali was proposed [21,22] for diperiodatonickelate (IV).

Os(VIII) is known to form different complexes at different OH$^-$ [23] concentrations $[OsO_4(OH)_2]^{2-}$ and $[OsO_5(OH)]^{3-}$. At higher concentration of OH$^-$, $[OsO_5(OH)]^{3-}$ is significant. At lower concentrations of as employed in present study, and since the rate of oxidation increased with increase in [OH$^-$], it is reasonable that $[OsO_4(OH)_2]^{2-}$ was operative and its formation is important in the reaction. To explain the observed orders the following Scheme **2** is proposed for osmium(VIII) catalysed reaction.

In the prior equilibrium step 1, the [OH⁻] deprotonates the DPA to give a deprotonated diperiodatoargentate(III); in the second step, displacement of a ligand, periodate takes place to give free periodate which is evidenced by decrease in the rate with increase in [periodate] (Table **1**). It may be expected that a lower Ag(III) periodate species such as MPA is more important in the reaction than the DPA. In the pre-rate determining stage, the Os(VIII) species combines with a molecule of anionic species of DFS to give an intermediate complex (C), which further reacts with one molecule of MPA which decomposes in a slow step to give the free radical derived from DFS, Ag(II) species and regeneration of catalyst, osmium(VIII). This free radical of DFS combines with Ag (II) species in a fast step to give an [2-(2, 6-dichloro-phenylamino)-phenyl]-methanol. Thus, all these results indicate a mechanism of the type as in Scheme **2**.

The probable structure of complex (C) is given in Scheme **3**.

Spectroscopic evidence for the complex formation between Os(VIII) and DFS was obtained from UV-vis spectra of DFS (5.0×10^{-4}), Os(VIII) (8.0×10^{-6}), [OH⁻] = 0.5(mol dm⁻³) and mixture of both. A bathochromic shift of about 6nm from 242 to 248 nm in the spectra of Os(VIII) and hyperchromicity at 248 nm was observed. The Michaelis-Menten plot also proved the complex formation between Os(VIII) and DFS, which explains the less than unit order dependence on DFS. Such type of complex between substrate and catalyst has been observed in other studies [24]. A unique isobestic point, observed at 410nm, indicates the presence of single complex. Scheme **2** leads to the following rate law (6).

$$ \text{Rate} = \frac{-d\,[\text{DPA}]}{dt} $$

$$ = \frac{k\,K_1 K_2 K_3\,[\text{DPA}][\text{DFS}][\text{OH}^-][\text{Os(VIII)}]}{[\text{H}_3\text{IO}_6{}^{2-}] + K_1[\text{OH}^-][\text{H}_3\text{IO}_6{}^{2-}] + K_1 K_2[\text{OH}^-] + K_3[\text{DFS}][\text{H}_3\text{IO}_6{}^{2-}] + K_1 K_3[\text{DFS}][\text{OH}^-][\text{H}_3\text{IO}_6{}^{2-}] + K_1 K_2 K_3[\text{OH}^-][\text{DFS}]} \quad (6) $$

The terms $K_3[\text{H}_3\text{IO}_6{}^{2-}][\text{DFS}]$ and $K_1 K_3[\text{DFS}][\text{OH}^-][\text{H}_3\text{IO}_6{}^{2-}]$ of denominator of eq. (6) can be neglected in the view of low concentrations of DFS and periodate used in study.

Therefore, eq. (6) becomes

$$ \frac{\text{Rate}}{[\text{DPA}]} = k_C = k_T - k_U $$

$$ = \frac{k K_1 K_2 K_3\,[\text{DFS}][\text{OH}^-][\text{Os(VIII)}]}{[\text{H}_3\text{IO}_6{}^{2-}] + K_1[\text{OH}^-][\text{H}_3\text{IO}_6{}^{2-}] + K_1 K_2[\text{OH}^-] + K_1 K_2 K_3[\text{DFS}][\text{OH}^-]} \quad (7) $$

which explains all the observed kinetic orders of different species. The rate law (7) can be rearranged to eq. (8), which is suitable for verification.

$$ \frac{[\text{Os(VIII)}]}{k_C} = \frac{[\text{H}_3\text{IO}_6{}^{2-}]}{k K_1 K_2 K_3[\text{DFS}][\text{OH}^-]} + \frac{[\text{H}_3\text{IO}_6{}^{2-}]}{k K_2 K_3[\text{DFS}]} + \frac{1}{k K_3[\text{DFS}]} + \frac{1}{k} \quad (8) $$

According to equation (8), plots of [Os(VIII)]/k_C *vs* 1/[OH⁻], [Os(VIII)]/k_C *vs* 1/[DFS] and [Os(VIII)]/k_C *vs* [H₃IO₆²⁻] were linear as in Fig. (**5**). From the slopes and intercepts of such

plots, the reaction constants, K_1, K_2, K_3 and k were calculated as (0.20 ± 0.008) dm³mol⁻¹, $(1.03 \pm 0.05) \times 10^{-4}$ mol dm⁻³, $(2.60 \pm 0.12) \times 10^3$ dm³ mol⁻¹ and $(5.28 \pm 0.12) \times 10^2$ dm³ mol⁻¹ s⁻¹ respectively. The values of K_1 and K_2 obtained were in good agreement with previously reported values [24]. These constants were used to calculate the rate constants and compared with experimental k_C values and found to be in reasonable agreement with each other, which fortifies the Scheme **2**. The equilibrium constant K_1 is far greater than K_2 which may be attributed to the greater tendency of DPA to under go deprotonation compared to the formation of hydrolysed species in alkaline medium.
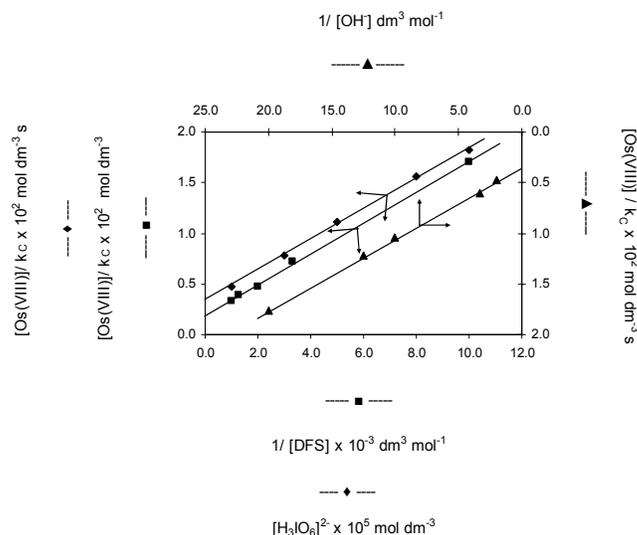

Fig. (5). Plot of verification of rate law Eq. (7) in the form of Eq.(8) of Os(VIII) catalysed oxidation of diclofenac sodium by diperiodatoargantate (III) in aqueous alkaline medium at 25°C.

The thermodynamic quantities for the first, second and third equilibrium steps of Scheme **2** can be evaluated as follows. The DFS, OH⁻ and IO₄⁻ concentrations (Table **1**) were varied at different temperatures. The plots of [Os(VIII)]/k_C *vs* 1/[DFS] (r ≥ 0.999), [Os(VIII)]/k_C *vs* [H₃IO₆²⁻] (r ≥ 0.999), [Os(VIII)]/k_C *vs* 1/[OH⁻] (r ≥ 0.999) were linear as shown in Fig. (**5**). From the slopes and intercepts, the values of K_1 were calculated at different temperatures. A vant Hoff's plots were made for variation of K_1 with temperature [i.e., log K_1 *vs* 1/T (r ≥ 0.9958)] and the values of enthalpy of reaction ΔH, entropy of reaction ΔS and free energy of reaction ΔG, were calculated. These values are given in Table **2**. A comparison of ΔH value (50.5 ± 2.5) from K_1 with that of ΔH# (24.2 ± 1.2) of rate limiting step supports that the first step of Scheme **2** is fairly slow since it involves high activation energy [25]. In the same manner, K_2 and K_3 values were calculated at different temperatures and the corresponding values of thermodynamic quantities are given in Table **2**.

The effect of ionic strength and dielectric constant on the rate of the reaction qualitatively explains the involvement of a neutral species as given in Scheme **2**.

The values of ΔH# and ΔS# were both favourable for electron transfer processes. The favourable enthalpy was due to release of energy on solutions changes in the transition state. The negative value of ΔS# indicates that the intermediate complex (C) is more ordered than the reactants [26]. The observed modest enthalpy of activation and a higher rate constant for the slow step indicates that the oxidation

presumably occurs *via* an inner-sphere mechanism. This conclusion is supported by early observations [27]. The activation parameters evaluated for the catalysed and uncatalysed reaction explain the catalytic effect on the reaction. The catalyst Os(VIII) form the complex (C) with substrate which enhances the reducing property of the substrate than that without catalyst. Further, the catalyst Os(VIII) modifies the reaction path by lowering the energy of activation.

5. CONCLUSION

The Os(VIII) catalysed oxidation of DFS by diperiodatoargentate(III) was studied. Oxidation products were identified. Among the various species of Ag(III) in alkaline medium, in earlier reports the diperiodatoargentate(III) was the active species, whereas monoperiodatoargentate(III) itself is considered to be active species for the title reaction. Active species of Os(VIII) is $[OsO_4(OH)_2]^{2-}$. Activation parameters were evaluated. Catalytic constants and the activation parameters with reference to catalyst were also computed.

APPENDIX

$$\text{Rate} = \frac{-d\,[DPA]}{dt} = k\,[C]\,[Ag] = \frac{k\,K_1 K_2 K_3\,[DFS]_f\,[Os(VIII)]_f\,[DPA]_f\,[OH^-]_f}{[H_3IO_6^{2-}]} \tag{I}$$

$$[DPA]_T = [DPA]_f + [Ag]^{2-} + [Ag]$$

$$[DPA]_T = [DPA]_f\left\{1 + K_1\,[OH^-] + \frac{K_1 K_2\,[OH^-]}{[H_3IO_6^{2-}]}\right\}$$

$$[DPA]_f = \frac{[DPA]_T\,[H_3IO_6^{2-}]}{[H_3IO_6^{2-}] + K_1[OH^-]\,[H_3IO_6^{2-}] + K_1 K_2\,[OH^-]} \tag{II}$$

where $[Ag]^{2-} = [Ag(H_2IO_6)(H_3IO_6)]^{2-}$, $[Ag] = [Ag(H_2IO_6)(H_2O)_2]$ subscripts T and f stand for total and free concentrations respectively.

Similarly,

$$[Os(VIII)]_T = [Os(VIII)]_f + [C] = [Os(VIII)]_f\left\{1 + K_3\,[DFS]\right\}$$

$$[Os(VIII)]_f = \frac{[Os(VIII)]_T}{1 + K_3\,[DFS]} \tag{III} \qquad [DFS]_f = \frac{[DFS]_T}{1 + K_3\,[Os(VIII)]} \tag{IV}$$

In eq. (IV) low concentrations of osmium(VIII) used, so the term $1 + K_3\,[Os(VIII)]$ is neglected. Therefore,

$$[DFS]_f = [DFS]_T \tag{V} \qquad \text{Similarly,} \qquad [OH^-]_f = [OH^-]_T \tag{VI}$$

Substituting eq. II, III, V and VI in eq. I, we get

$$\frac{-d\,[DPA]}{dt} = \frac{k\,K_1 K_2 K_3\,[DPA][DFS][OH^-][Os(VIII)]}{[H_3IO_6^{2-}] + K_1\,[OH^-][H_3IO_6^{2-}] + K_1 K_2\,[OH^-] + K_3\,[DFS][H_3IO_6^{2-}]} \tag{VII}$$
$$+ K_1 K_3\,[DFS][OH^-][H_3IO_6^{2-}] + K_1 K_2 K_3\,[OH^-][DFS]$$

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