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CATALYTIC OXIDATION OF FURAN AND HYDROFURAN COMPOUNDS

8*. SYNTHESIS OF 5-ETHOXYCARBONYL-4-HYDROXY-3-OXO-2(3H)-FURANONE BY THE OXIDATION OF FURFURAL IN THE SYSTEM AQUEOUS H_2O_2–$VOSO_4$–ETHANOL

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The special features of the oxidation of furfural by aqueous hydrogen peroxide in the presence of vanadyl sulfate and ethanol has been studied for the first time. It has been established that this reaction proceeds with the formation of previously unknown oxidation products of furan compounds, one of which was isolated from the reaction mixture as the ethyl ester. It was established by spectral methods and qualitative reactions that this product is 5-ethoxycarbonyl-4-hydroxy-3-oxo-2(3H)-furanone.

Keywords: hydrogen peroxide, furfural, vanadium catalyst, oxidation.

It was established previously that the oxidation of furan compounds by aqueous hydrogen peroxide in the presence of vanadium catalyst is a complex multidirectional process [2, 3]. The main factors influencing the composition of the resulting products are the nature of the substituent in the furan nucleus and the type of organic solvent used [2, 4-6]. On studying the joint action of these and other factors conditions emerged for the oxidation of furfural **1** and furan **2** leading to the preferential formation of known poorly available products, *viz*. 5-hydroxy-2(5H)-furanone (**3**) and its derivatives [7-9], succinic acid [2], furan-2-carboxylic acid amide [2], and 2,5-diethoxy-2,5-dihydrofuran (**4**) [10, 11]. It turned out that addition of ethanol to the system for oxidizing compound **2** assisted acceleration of the process and of the accumulation of its intermediate products, dialdehydes, polyacetals, and carboxylic acids, as a result of their partial binding into the corresponding acetals and esters.

It seemed of interest in this connection to study the possibility of broadening the synthetic possibilities of oxidizing aldehyde **1** with aqueous hydrogen peroxide in the presence of a compound of vanadium (IV, V) by introducing ethanol or butanol into the reaction medium. Reactions of furfural with H_2O_2 in systems simultaneously containing metal-containing catalysts and alcohol have not been studied previously.

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* For Communication 7 see [1].

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TABLE 1. Results of the Oxidation of Furfural **1** with Aqueous H_2O_2 in the Presence of $VOSO_4$ in Aqueous and Aqueous-alcoholic Media at 60°C (**1**:H_2O_2:$VOSO_4$ = 1: 3.2:0.005; [**1**]$_{init}$ = 1.2 M)

Expt. No.	Cosolvent	Extent of furfural conversion, %	$\tau_{½}$, min	Time for complete consumption of H_2O_2, h	Products, %*				
					Acids				Furanone
					5 + 6	**7 + 8**	**9**	**12**	**10**
1	–	100	42	6.5	40	9	12	< 1	8
2	EtOH	87	29	2.5	21	6	10	13	8
3	EtOH	100*^{2}	–*^{3}	3	15	5	8	11	6
4	*n*-BuOH	40	37	6	< 1	< 1	16	9	10

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* Of reacted furfural.

*^{2} Reached in the presence of 3.5 mol H_2O_2 per mol furfural.

*^{3} Not determined.

The oxidation of aldehyde **1** in aqueous alcoholic media was carried out in comparison with its previously studied reaction in water. Vanadyl sulfate was used as catalyst, existing in aqueous solutions of H_2O_2 as peroxy complexes of vanadium (V). The catalyst was taken in an amount previously selected for the oxidation of compound **1** with aqueous hydrogen peroxide. The reaction conditions are given in Table 1.

In experiments 2-4 in place of the calculated amount of water the same volume of ethanol or 1-butanol was introduced into the reaction mixture.

It was discovered that the catalytic oxidation of furfural in aqueous solutions of alcohols differs substantially from its reaction in water. For complete conversion of aldehyde **1** (1 mol) in water (expt. 1) 3.2 mol H_2O_2 was required, while in the presence of alcohols (expt. 2 and 4) at this ratio the extent of conversion was significantly lower. For complete conversion of 1 mol furfural in aqueous ethanol (expt. 3) 3.5 mol H_2O_2 was required.

It is characteristic that on introducing ethanol a significant acceleration of the process was observed, while in the presence of 1-butanol this acceleration was insignificant.

The chief products of oxidation of furfural in the system aqueous H_2O_2–$VOSO_4$ were C_4 carboxylic acids (Table 1, expt. 1). The main product was *cis*-β-formylacrylic acid (**5**), isolated as the tautomeric furanone **3** by the procedure developed by us previously [2, 8, 12]. The *trans*-isomer of β-formylacrylic acid (**6**), maleic and fumaric acids (**7**) and (**8**), succinic acid (**9**), 2(5H)-furanone (**10**) accumulated in lesser amounts. Yields of these compounds were established by known chromatographic and polarographic methods [2, 8, 12].

On adding alcohols the overall yield of these products was reduced from 70 to 35-45% (expt. 2-4), and on increasing further the amount of organic solvent approached zero. This occurred primarily as a result of a sharp fall in the yield of acid **7**. Notably, a fall was also observed in the yield of an important side product of aldehyde **1** oxidation, formic acid (**11**), formed as a result of oxidative cleavage of the C–C bond between the heterocycle and the substituent [2, 13, 14]. Simultaneously, as might have been expected on the basis of the results of [13, 14], the yield of furan-2-carboxylic acid (**12**) was significantly increased in expt. 2-4.

On the basis of studies [15-17] it was assumed that alcohols in the H_2O_2–vanadium compound system would be oxidized to the corresponding aldehydes and carboxylic acids. It was established by GLC and qualitative reactions that these compounds are in fact formed in experiments 2-4, however their yields did not exceed 2-5%.

It was established by TLC that the main conversion products of furfural in the system H_2O_2–$VOSO_4$–alcohol are new compounds not formed under other conditions of oxidizing furans. A mixture of these products

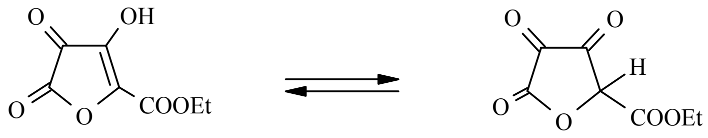
TABLE 2. Spectral Characteristics of Furanone **13**

Compound	IR spectrum, ν, cm^{-1}	^{1}H NMR spectrum, δ, ppm (*J*, Hz)	Mass-spectrum, *m/z* (*I*, %)
13a + **13b**	1160–1260 (C–O–C), 1630 (C=C), 1710, 1715 (C=O$_{ketone}$), 1730 (C=O$_{ester}$), 1770, 1745 (C=O$_{lact}$), 3500 (OH)	1.22 (3H, t, *J* = 7, CH_3); 4.08 (2.5–2.8 H, m, OCH_2 + H-5); 6.20–7.10 (0.2–0.5 H, very br., OH)	186 [M]$^+$ (0.3), 144 (11), 130 (29), 129 (11), 128 (13), 127 (21), 101 (52), 100 (41), 99 (23), 83 (15), 73 (21)

was obtained by concentrating the oxidation products from experiment 3 and was a very viscous substance crystallizing with difficulty. It readily resinified under conditions of distillation under reduced pressure. On interacting with NaOH or Na_2CO_3 solution the new products formed salts, which enabled them to be assigned to the class of carboxylic acids.

The acids obtained by the oxidation of aldehyde **1** in aqueous ethanol were therefore converted to their esters. For this, the water was removed from the alcoholic oxidation products by azeotropic distillation, ethanol was added, and esterification of the acid products was carried out by the usual procedure. The main component of the mixture formed was obtained in a pure state by distillation under reduced pressure. The spectral characteristics of this compound are given in Table 2.

The spectral data form a basis for proposing that the product isolated is 5-ethoxycarbonyl-4-hydroxy-3-oxo-2(3H)-furanone (**13**) existing in the tautomeric forms **13a** and **13b**:

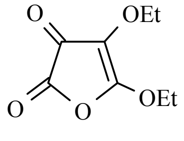


13a **13b**

A series of strong bands was present at 1710-1770 cm^{-1} in the IR spectrum of product **13** indicating the presence in its molecule of ketone, ester, and lactone oxogroups. The presence of a hydroxyl group and a C=C bond was also confirmed by absorption maxima (Table 2). The presence of bands corresponding to the C–O–C grouping indicates the cyclic form of the molecule of ester **13**.

Signals were present in the ^{1}H NMR spectrum of product **13** caused by the resonance of protons of methyl and hydroxyl groups. A multiplet observed at 4.08 ppm is evidently caused by the overlap of signals of CH_2 group protons and the proton at position 5 of furanone **13b**. The ratio of the intensities of the signals of this multiplet and of the OH group changes depending on the concentration of compound **13** and the type of solvent (CCl_4, $CHCl_3$, $CO(CD_3)_2$), which may be explained by the change in intensity of the H-5 signal as a result of displacement of the equilibrium between the keto–enol tautomers of ester **13**. This indicates that 20-50% molecules of the obtained ester may be in the enolic form **13a**.

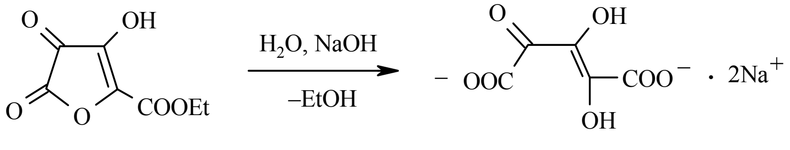
A molecular ion of mass 186 m.u. was present in the mass spectrum of compound **13**. The ion of *m/z* 29 had maximum intensity. The other most stable fragment ions are given in Table 2.



14

Among the theoretically possible oxidation products of aldehyde **1** only compounds **13** and **14** may have a molecular ion of mass 186 a.m.u., however the structure of the latter substance does not correspond to the data of elemental analysis, IR and NMR spectroscopy.

Additional proof in favor of the existence of the isolated product in the form of structures **13a** and **13b** was obtained with the aid of qualitative reactions. An ethanolic solution of compound **13** instantly acquired an intense dark yellow-orange color on adding a 1% solution of $FeCl_3$, which indicated the presence of the enolic group. The presence of a 1,2-diketone grouping was confirmed with the aid of known procedures [18] (positive reaction with hydroxylamine and $NiCl_2$ in ammonia vapor, the formation of colored complexes with thiophene). The presence of a C=C bond was confirmed by the instant decolorization of bromine water on adding an alcoholic solution of product **13** to it. Ester **13** did not interact with an aqueous solution of $AgNO_3$, which indicates the absence of an enediol grouping in its tautomeric forms. However this reaction proceeds rapidly in alkaline medium, which may be explained by the facile hydrolysis and fission of the lactone ring of compound **13** at pH >7.



13a

The predominance of tautomeric form **13a** may be explained by the presence in the compound **13** molecule of electron-withdrawing substituents stabilizing the enolic grouping [19, 20].

The structure considered above for ester **13** enables the suggestion that one of the main products of furfural oxidation in the system aqueous H_2O_2–$VOSO_4$–ethanol is 5-carboxy-4-hydroxy-3-oxo-2(3H)-furanone (**15**).

The change in the direction of furfural oxidation under the studied conditions in comparison with water may be linked with the ability of alcohols to facilitate cleavage of bonds in peroxide molecules and to increase the effective charge of vanadium(V) ions [21. 22].

It is noteworthy that acid **12** is oxidized significantly more slowly than furfural in aqueous alcoholic media. This permits the suggestion that it is not the main intermediate in the process of forming product **15**.

EXPERIMENTAL

The IR spectrum of compound **13** was taken on a Specord-40 M spectrometer (Germany) in nujol (NaCl and KBr prisms in the region of 800-3800 cm^{-}), the ^1H NMR spectrum on a Bruker WM 200 (250 MHz) instrument in CCl_4, internal standard was TMS, and the mass spectrum on a CH-6 instrument with direct insertion of substance into the ion source at an ionization energy of 70 eV, emission current 10 mA, and temperature 120°C. TLC of reaction mixtures and of the isolated product **13** were obtained on Silufol UV-254 plates in chloroform or in the system chloroform–acetone, 3:1. Visualization was with acidified $KMnO_4$ solution and 2,4-dinitrophenylhydrazine, with an alcoholic solution of bromophenol blue, and with iodine vapor.

The yields of carboxylic acids **5-9** (as their ethyl esters) and furanone **10** were determined by GLC. Esters of acids were obtained by boiling concentrates of reaction mixtures in the system ethanol–chloroform–benzenesulfonic acid (see procedure for the synthesis of compound **13**). Analysis of esterification products was carried out on a Chrom-4 instrument (Czechoslovakia) with a flame-ionization detector, and a glass column (300×0.3 cm) containing 15% polymethylphenylsiloxane oil (PMPS-4) on chromaton N-AW DMCS. Column, evaporator, and detector temperatures were 150, 220, and 220°C respectively. Carrier gas was nitrogen at

30 ml/min. The retention times of furanone **10**, 5-ethoxy-2(5H)-furanone (product of interaction of acid **5** with ethanol), diethyl esters of fumaric and maleic acids, were 2.62-2.75, 4.15-4.30, 5.30-5.50, and 6.35-6.50 min respectively. The same chromatographic conditions were used for determining the yields of the oxidation products of ethanol and 1-butanol.

The contents of isomers of β-formylacrylic acid **5** and **6**, maleic and fumaric acids **7** and **8,** in reaction mixtures were determined by polarography. A sample was taken from the reaction mixture (0.5 ml) obtained in experiments 1-4 and was dissolved in background electrolyte (0.1 M $HClO_4$ or pH 7.4 phosphate buffer solution) made up to volume (50 ml), and stirred. Samples were analyzed in 1 day on a LP-70 polarograph in a thermostatted cell with a dropping mercury electrode (m = 1.59 mg/sec; t = 3.66 sec at a potential of -1.0 V, and 25 ± 0.2°C), the reference electrode was a normal calomel electrode. Half wave potentials for the reduction of compounds **5-8** in 0.1 M $HClO_4$ were 0.38-0.40 (for isomers **5** and **6**) and 0.67 V (for isomers **7** and **8**). The half wave potential for the reduction of compounds **7** and **8** in phosphate buffer mixture was 1.45-1.50 V. The concentrations of the substances being determined in the samples were established with a calibration graph.

Procedure for the Oxidation of Furfural. Experiment 1. Furfural (5 ml, 0.060 mol) was added to a solution of $VOSO_43H_2O$ (0.064 g, 3.10^{-4} mol) in water (30.3 ml) and 38.5% H_2O_2 (14.7 ml, 0.192 mol), and stirred at 60°C until complete conversion of H_2O_2 and the resulting organic peroxides (absence of color reaction with KI solution).

Experiments 2-4 were carried out by the procedure of experiment 1, in place of the indicated amount of water the same volume of ethanol or 1-butanol was added.

Synthesis of 5-Ethoxycarbonyl-4-hydroxy-3-oxo-2(3H)-furanone (**13**). A solution of furfural (15 ml, 0.18 mol) and $VOSO_43H_2O$ (0.192 g, $9.1\cdot10^{-4}$ mol) in 37.5% H_2O_2 (135 ml, 1.56 mol) and ethanol (300 ml) was stirred at 60°C for 12 h. The solvent was removed, ethanol (30 ml), chloroform (60 ml), and benzenesulfonic acid (0.5 g) were added to the residue. The mixture was boiled with azeotropic distillation of water for 10-12 h, evaporated, extracted with ether, washed with $NaHCO_3$ solution, and with water, dried over Na_2SO_4, distilled under reduced pressure, and ester **13** obtained in 23% yield (from the initial furfural). Bp 167-172° (18 mm Hg). Found, %: C 45.16; H 3.22. $C_7H_6O_6$. Calculated, %: C 45.23; H 3.11.

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