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Catalytic Oxidations. I. Oxidations in the Furan Series

BY NICHOLAS A. MILAS AND WILLIAM L. WALSH

Introduction

The catalytic oxidation of furfural and furoic acid in aqueous chlorate solution, using vanadium pentoxide or osmium tetroxide as the catalyst, yields chiefly fumaric acid with the former and mesotartaric acid with the latter catalyst.¹ The catalytic oxidation of furan and its derivatives, using air or oxygen at somewhat elevated temperatures, has not been investigated adequately. Sessions² has made a qualitative study of the vapor-phase oxidation of furfural but reported only small yields of maleic acid.

The aim of the present communication is two-fold: (1) to describe a general technique for the catalytic oxidation of organic substances of low volatility or substances which polymerize or resinify easily before they come in contact with the catalyst, and (2) to apply this improved technique to a quantitative study of the catalytic oxidation of furan, furfural, furfuryl alcohol and furoic acid.

Experimental Part

1. **The Apparatus.**—Figure 1 shows diagrammatically the apparatus used in the present study. It is made up of a vertical, well-insulated furnace A containing an iron core B which is wound with chromel A resistance wire insulated in the usual manner. The reaction tube C consists of a Pyrex tube 78 cm. long by 23 cm. in cross section, which is indented at O in order to support the catalyst P.

The addition of the substance to be oxidized is measured accurately by the buret E, and is controlled by a 25-cm.

length Pyrex capillary of 0.5 mm. cross section which is wound into spiral D, and by the tube S which serves to keep the rate of flow constant. Variations in the rate of addition (1–10 cc. per hour), as indicated by the calibrated mercury manometer I, may be secured by raising the mercury bulb J so that the pressure over the organic substance is increased. The air or oxygen flow is measured by the flowmeter F and the pressure in the reaction system is indicated by the mercury manometer G. Before they are introduced into the reaction system both air and oxygen are dried by passing them through concentrated sulfuric acid, then through soda lime and anhydrous calcium chloride. The tube R is bent in such a way that the substance to be oxidized drops directly upon it and thus is blown into a spray by the incoming stream of air or oxygen.

For the introduction of solids a Pyrex tube (2 × 20 cm.) constricted near the lower end to about 1 mm. in cross section and connected to the tube S by means of a rubber stopper is substituted for the buret. A mechanical vibrator serves to regulate the addition of the finely powdered solid, as well as to prevent the plugging of the capillary constriction.

The temperature of the furnace is regulated by a simple photoelectric device³ operated by a bare thermocouple K which is so arranged that it can be moved up and down to any portion alongside the catalyst chamber. The leads M and N are connected to the potentiometer and thermostat, respectively.

All condensable products at the temperature of carbon dioxide ice were collected in the flask and two traps shown in Fig. 1 all of which were connected to the reaction tube C by means of ground joints and immersed in carbon dioxide ice freezing mixture. The additional trap shown in the same figure contained water which served to catch small amounts of water-soluble products which escaped the other traps.

(1) Milas, *THIS JOURNAL*, **49**, 2005 (1927).

(2) Sessions, *ibid.*, **50**, 1696 (1928).

(3) Walsh and Milas, *Ind. Eng. Chem., Anal. Ed.*, **7**, 122 (1935).

2. The Catalysts.—The vanadium pentoxide catalyst employed was prepared as follows. To an aqueous solution containing 25 g. of pure ammonium metavanadate was added 100 g. of pumice (8–10 mesh) and the mixture evaporated to dryness with continuous stirring. The impregnated pumice was then heated in the reaction chamber at 350–375° for two hours while passing over it a rapid current of dry air. The brownish-red catalyst so formed was found to be too active for our purpose and had to be pretreated with a mixture of air and the substance to be oxidized for a period of four to five hours. This treatment produced a catalyst of a blue-black appearance having uniform activity which could easily be duplicated. No decline in the activity of the catalyst has been observed in any of our experiments, and it remained active indefinitely provided the temperature of the reaction was kept within the limits employed.

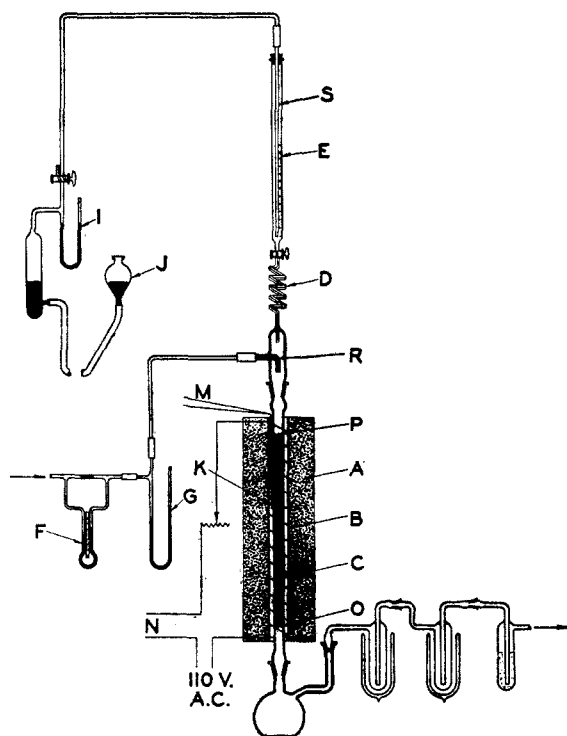


Fig. 1.—Apparatus for catalytic oxidations.

The molybdenum oxide–vanadium pentoxide catalyst was prepared by adding the calculated amount of ammonium molybdate to ammonium metavanadate so that the final product contained 10% molybdenum oxide and 90% vanadium pentoxide by weight.

The bismuth vanadate was prepared by adding the calculated amount by weight of bismuth chloride to ammonium metavanadate and treating the mixture as before.

3. Organic Materials.—The furfural⁴ and furfuryl alcohol were purified by fractional distillation under reduced pressure and the fractions boiling at 53–55° (17 mm.) and 74–76° (17 mm.), respectively, collected and used in the experiments.

(4) The furfural used in these experiments was kindly furnished by the Quaker Oats Company.

The commercial furoic acid was recrystallized from a hot mixture of two parts of carbon tetrachloride and one part of chloroform and the product obtained melted at 132–133°.

The furan used was prepared in 70–75% yields by distilling crude furoic acid through the reaction tube described in Fig. 1 containing pumice instead of the catalyst and maintained at about 350°. The crude furan was fractionated and the fraction boiling at 30–32° collected and used in the experiments.

4. Analytical Procedure.—In the average run about 10 cc. of the liquid or 5 g. of the solid to be oxidized was introduced at constant rate over a period of from four to five hours. Since maleic acid and its anhydride were the chief products of interest that could be isolated, the extent of the oxidation, under various conditions, was followed by the quantitative estimation of the acid. In addition to these products, formaldehyde, carbon dioxide and unoxidized products were also identified.

At the completion of the run, air or oxygen was allowed to sweep through the catalyst chamber for ten to fifteen minutes longer. The traps were then disconnected and thoroughly washed with distilled water, the washings combined, diluted to a definite volume and aliquot portions titrated against standard solution of barium hydroxide to estimate the total acidity. In the case of furfural and furfuryl alcohol the combined washings were first extracted with three 10-cc. portions of carbon tetrachloride to remove small amounts of unoxidized furfural which was then estimated by the method of Jolles.⁵

Although the total acidity of the solution can, in certain cases, be attributed solely to maleic acid, this does not hold in every case, and a more trustworthy method based on the precipitation of maleic acid as barium maleate had to be devised. Under these conditions the barium furoate, if present, will remain in solution as indicated by blank determinations. The procedure finally adopted was as follows.

To 10-cc. portions of the final solution was added a slight excess of the equivalent amount of solid barium chloride; the resulting solution was made alkaline to litmus with concentrated ammonium hydroxide, diluted to three times its volume with 95% alcohol and the precipitate collected, dried at 110° and weighed as the monohydrate.⁶ The purity of the barium salt so obtained was proved by the quantitative conversion to barium sulfate in the usual manner.

Anal. Calcd. for $C_4H_2O_4Ba \cdot H_2O$: Ba, 51.02. Found: Ba, 51.00, 51.1.

Further proof that the solid acid formed was maleic acid was shown by its conversion to fumaric acid under the influence of light in the presence of bromine.

5. Discussion of Results

The technique and the method of analysis outlined in the foregoing sections were applied first to a study of the oxidation of furfural using vanadium pentoxide, bismuth vanadate and mixed catalyst, 10% molybdenum oxide—90% va-

(5) Jolles, *Z. anal. Chem.*, **45**, 196 (1906).

(6) Kempf, *J. prakt. Chem.*, [2] **83**, 337 (1911).

nadium pentoxide. Figure 2 shows the effect of the molal ratio of air to furfural, expressed in moles of air per moles of furfural passed through the catalyst per hour, on the percentage yield of maleic acid obtained at temperature intervals of 30° from 290 to 410°, keeping the time of contact between 3.6 to 6 seconds. The time of contact in all of our experiments has been calculated as the ratio between the volume of the catalyst space to the volume of the gas passing through the catalyst per second at the temperature of the reaction. At lower temperatures small amounts of furfural go through unchanged while at higher temperatures no furfural is recovered, and beyond a certain molal ratio the yield of maleic acid begins

to fall off. In all cases, however, considerable amounts of furfural resin or polymer appeared in the lower end of the reaction tube. Under the most favorable conditions, 320° and a molal ratio of 180, the yield of maleic acid was only 25%. Failure to exceed this limit is due, in our opinion, to the polymerization of furfural thereby producing polymers the oxidation of which may proceed by a different mechanism. This opinion is strengthened by the fact that furoic acid, oxidized under similar conditions, gives almost twice the yield obtained from furfural. Furthermore, when maleic acid in water solution is passed through the tube under similar conditions only 35% of it is destroyed.

A series of over 15 runs was made at 320, 350, 380 and 410° to determine the influence of time of contact on the yield of maleic acid. It has been found that for the same temperature and approximately the same molal ratio, the yield of maleic acid does not vary appreciably and is maximum at contact times of 3.6 to 6.0 seconds, but decreases considerably at contact times of 1 second or less. All of our experiments, therefore, were performed at contact times of 3.6 to 6.0 seconds.

Substitution of oxygen for air resulted in approximately the same yields of maleic acid, although the reaction proceeds at lower temperatures, 280° being the optimum temperature for

best yields. At molal ratios lower than 40 and at temperatures higher than 280° oxygen led invariably to explosions. At 250° the yields of maleic acid were distinctly lower. At this temperature water has a decided influence on the yield of maleic acid. In several runs oxygen saturated with water vapor at room temperature was found to double the yield at the molal ratio of 20, but as the latter increased the increase in yield became smaller until at molal ratios of 80 or above the yield with moist oxygen approached that with the dry oxygen. Larger amounts of water introduced simultaneously with the furfural, by means of a second buret, had no greater effect. Likewise, saturation of air with water vapor in other

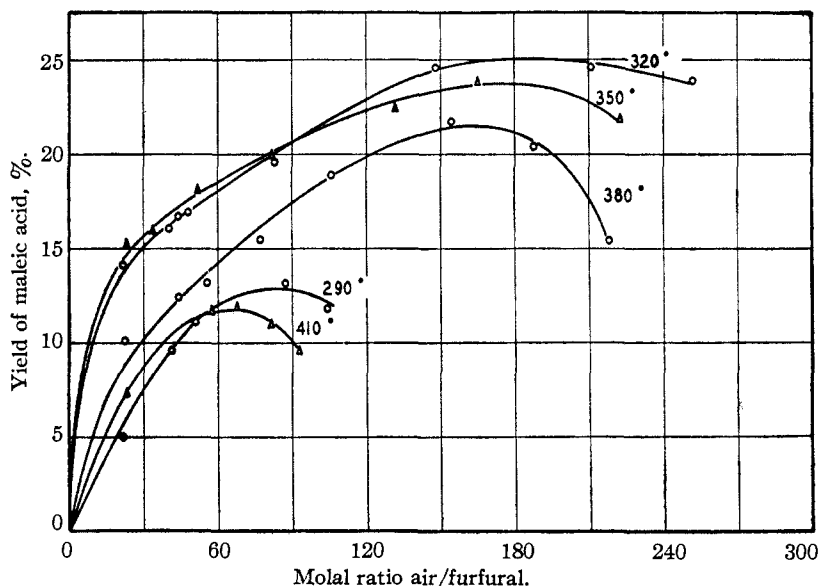


Fig. 2.—The effect of molal ratio of air to furfural on the yield of maleic acid at different temperatures.

experiments produced the same result as in the case with oxygen.

A series of runs were then made to study the effect of temperature on the yield of maleic acid at constant molal ratios of 80 of oxygen/furfural, and of 113 of air/furfural. With oxygen the maximum yields were obtained at about 280°, while with air the best yields were obtained over a range between 320–350°. The comparative amounts of oxygen and air necessary to give the same yield of maleic acid were likewise lower in the case of oxygen.

The effect of change in catalyst on the yield of maleic acid was briefly studied and it was found that with bismuth vanadate the maximum yield obtained was 24.2%, which is slightly lower than

that obtained with pure vanadium pentoxide. The optimum temperature, however, was 30° lower than in the case of vanadium pentoxide. With the mixed catalyst, 10% molybdenum tri-

oxide it may be of interest to compare the yields of maleic acid obtained from furan, in the present investigation, with those obtained from benzene by Weiss and Downs.⁷ These investigators reported a yield of about 40%, while Zalkind and Zolotarev,⁸ in reinvestigating the catalytic oxidation of benzene, gave 14-17% maleic acid as the best yield obtainable. Although benzene may be more economical than furan, the latter may be obtained easily in relatively high yields directly from furfural by the recent method of Hurd, Goldsby and Osborne.⁹

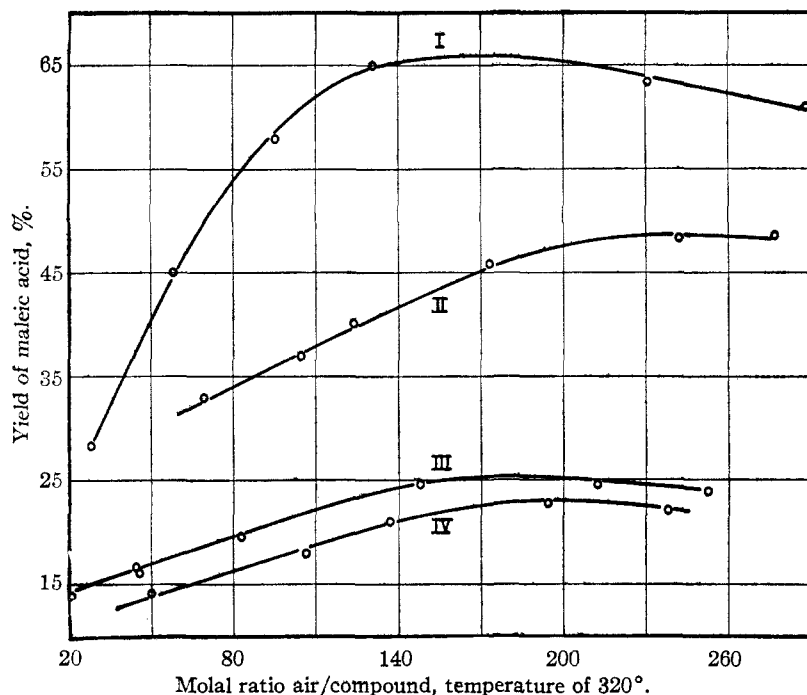


Fig. 3.—The effect of molal ratio of air to compound oxidized on the yield of maleic acid: I, furan; II, furoic acid; III, furfural; IV, furfural alcohol.

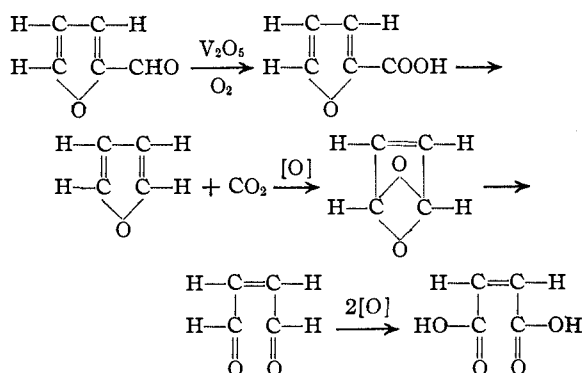
oxide-90% vanadium pentoxide, the yield of maleic acid was lower, and an increase of the molybdenum trioxide in the mixture to 35% was found to decrease the yield still further.

Most of the attention in this investigation has naturally been centered on furfural as the most important member in the furan series. However, other members of the series including furfuryl alcohol, furoic acid and furan were similarly oxidized and the results of a series of runs with each substance are plotted in Fig. 3. The highest yields were obtained with furan (curve I) which gave a maximum yield of 65% at a molal ratio of 130. Furoic acid (curve II) came next with a maximum yield of 48.4% at a molal ratio of 242. At a molal ratio of 188 furfuryl alcohol gave a maximum yield of 22.5%, which is lower than that obtained from furfural (curve III). Just as in the case of furfural there was considerable polymerization with furfuryl alcohol, which accounts for the low yields of maleic acid. Both furan and furoic acid, on the other hand, produced no observable polymers.

The Mechanism of Maleic Acid Formation

Since maleic acid is the main solid product resulting from the oxidation of furan, furfural, furfuryl alcohol and furoic acid, it is reasonable to assume that the mechanism of its formation is the same in all four cases. Using furfural as an example, the mechanism of the catalytic oxidation may be illustrated as follows

tion may be illustrated as follows



At temperatures of 250° or above maleic acid will exist as its anhydride which combines slowly with water in the traps to reform the acid. The 1,4-addition of the oxygen atom to the furan ring finds ample support in previous investigations,¹ and furnishes, in our opinion, the most reasonable

(7) Weiss and Downs, *J. Soc. Chem. Ind.*, **45**, 188-193T (1926).

(8) Zalkind and Zolotarev, *J. Applied Chem.* (U. S. S. R.), **6**, 681 (1933).

(9) Hurd, Goldsby and Osborne, *THIS JOURNAL*, **54**, 2532 (1932).

interpretation of the catalytic oxidation of the furan ring.

Summary

1. An improved technique has been developed for the catalytic oxidation of organic substances especially of substances of low volatility.

2. The catalytic oxidation of furfural has been investigated under various conditions of temperature, molal ratio and time of contact using vanadium pentoxide as the catalyst. Bismuth

vanadate, and a mixed catalyst, 10% molybdenum oxide-90% vanadium pentoxide, were also used as catalysts.

3. The catalytic oxidation of furan, furfuryl alcohol and furoic acid has also been investigated.

4. In all cases maleic acid was the chief solid product formed in yields ranging from 65% from furan to 22.5% from furfuryl alcohol.

5. A mechanism of the oxidation has been proposed.

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A Synthesis of Conjugated Bile Acids. I. Glycocholic Acid

BY FRANK CORTESE AND LOUIS BAUMAN

We were interested in a practical method for the preparation of sizable quantities of the naturally occurring conjugated bile acids in a reasonable state of purity. Their isolation from the bile by available methods is an uncertain procedure; the yields are poor and the products of doubtful homogeneity.

The only synthetic method to be found in the literature is that of Bondi and Mueller,¹ who coupled the azide of cholic acid with glycine and taurine. This method did not appear to be particularly practical for our purposes. Moreover, we noted that Bondi and Mueller apparently did not obtain taurocholic acid in a crystalline state. Wieland² used the same method for the preparation of glycodeoxycholic and taurodeoxycholic acids, but he doubted their identity with the naturally occurring substances.

By protecting the hydroxyl groups of cholic acid with formyl groups, we were able to make the acid chloride, and this was coupled with glycine in alkaline solution. The new synthesis is cheap and gives a good over-all yield, 25-35 g. of glycocholic acid being obtained from 50 g. of crystalline cholic acid.

Experimental Part

Triformylcholic Acid.—A mixture of 50 g. of cholic acid, m. p. 202-203° (corr.) and 100 cc. of redistilled formic acid (sp. g. 1.20) was warmed at 50-55° for five hours and then evaporated to dryness under reduced pressure at the same temperature. To a boiling solution of the residue in 500

cc. of 95% alcohol, 600 cc. of water was added at such a rate that no precipitation occurred. The solution was allowed to cool with stirring until crystals appeared; after twenty-four hours at room temperature the product was filtered off, washed with an ice-cold mixture of 50 cc. of water and 60 cc. of 95% alcohol, and dried at 100°. The yield was 35-43 g. (60-75%). It was recrystallized, with little loss, from a mixture of 500 cc. of 95% alcohol and 600 cc. of water, from which it separated in rosetts of needles melting at 206-207° (corr.). Further recrystallization from benzene and petroleum ether failed to change the melting point.

Anal. Calcd. for $C_{27}H_{46}O_5$: C, 65.85; H, 8.13. Found: C, 66.03; H, 8.01.

The acid cannot be titrated accurately with dilute alkali owing to the susceptibility of the formyl groups to hydrolysis. 0.5599 g. on boiling for one hour with 25 cc. of alcohol and excess of 0.1 *N* sodium hydroxide consumed 44.76 cc. of the alkali (calcd. 45.51 cc.).

The use of stronger formic acid than that indicated did not improve the yield.

Triformylcholy Chloride.—A solution of 50 g. of pure triformylcholic acid (dried at 110° for five hours) in 50 cc. of freshly redistilled thionyl chloride was spontaneously evaporated in the hood under a strong draft after standing for one to three hours. The gummy residue was worked up with petroleum ether (30-60°) to a white powdery mass. After one more evaporation to dryness, it was washed with petroleum ether and air dried for about fifteen minutes. The yield was 49-51 g., or 95-98%.

The fresh material starts to discolor at about 125° and decomposes at about 147° (corr.) with weak foaming. After two days' exposure to the air, a sample was recrystallized from benzene and petroleum ether and was found to have been completely hydrolyzed to triformylcholic acid, as shown by a mixed melting point.

0.3658 g. of fresh material hydrolyzed as indicated above for triformylcholic acid consumed 35.15 cc. of alkali (calcd. 35.79 cc.).

(1) Bondi and Mueller, *Z. physiol. Chem.*, **47**, 499 (1906).

(2) Wieland, *ibid.*, **106**, 181 (1919).