

Research Article

Direct Benzyl Alcohol and Benzaldehyde Synthesis from Toluene over Keggin-Type Polyoxometalates Catalysts: Kinetic and Mechanistic Studies

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The catalytic activity of various Keggin polyoxometalate catalysts has been investigated in the gas-phase partial oxidation of toluene to produce benzyl alcohol and benzaldehyde. The catalyst systems $\text{HPMo}_{12}\text{O}_{40}$, $\text{HPMo}_{11}\text{VO}_{40}$, $\text{FePMo}_{12}\text{O}_{40}$, and $\text{PMo}_{11}\text{FeO}_{39}$ were prepared and characterized by FT-IR, UV-visible, SEM, XRD, TGA, and cyclic voltammetry. The acid/base properties were evaluated using the decomposition of isopropanol. Catalytic studies were carried under atmospheric pressure and over the temperature range 200°C – 350°C , using carbon dioxide as a mild oxidant. Toluene conversion and product distribution depend mainly on the catalyst composition and operating conditions. In addition to benzaldehyde, benzyl alcohol is obtained with a high selectivity on the $\text{PMo}_{11}\text{FeO}_{39}$ catalyst. The kinetic data show that the reoxidation of the reduced catalyst is the rate-limiting step for the partial oxidation reaction of toluene.

1. Introduction

Aromatic aldehydes such as benzaldehyde are very valuable industrial organic intermediates, and their uses include the manufacture of flavors, fragrances, pharmaceutical precursors, and plastic additives. Industrially, benzaldehyde is produced exclusively by the liquid phase oxidation of toluene [1, 2]. Usually, benzaldehyde is made by a process in which toluene is treated with chlorine to form benzal chloride, followed by treatment of benzal chloride with water. This process suffers from several problems, such as the formation of undesirable products, equipment corrosion with chlorine, and complex products' separation. An alternative is the gas-phase oxidation of toluene. However, toluene conversion and product distribution largely depended on catalyst composition and operating conditions. Vanadium oxide-based materials are the most commonly used catalysts in this process. Since the discovery of the effectiveness of vanadium pentoxide as catalyst in sulfur dioxide oxidation by Haen [3], in 1900, a considerable number of studies have been carried in homogeneous and

heterogeneous catalysis, such as the conversion of alkanes to the corresponding alkenes [4–7] and the conversion of alcohols to aldehydes or ketones [8–11]. Supported vanadium oxide catalysts are also used in gas-phase catalytic partial oxidation of toluene [12–14]. The supported vanadium-based catalysts were reported to show high benzaldehyde selectivity, but the toluene conversion was below 10% at the low temperature ($<400^{\circ}\text{C}$). However, at higher temperature ($>400^{\circ}\text{C}$), the toluene conversion increased and the selectivity to benzaldehyde decreased and those to carbon oxides increased. Other workers have reported that pure and mixed molybdenum oxides are very efficient in gas-phase partial oxidation of toluene [15]. The main reaction products were maleic anhydride, benzaldehyde, and carbon oxides [16]. The investigation of the influence of various metal oxides on the behaviour of molybdenum oxide towards the oxidation of toluene with molecular oxygen concluded that toluene oxidation decreases in the following order: support oxides \geq molybdenum oxide monolayer catalysts $>$ molybdate salts $>$ crystalline molybdenum oxide, but the benzaldehyde and

benzoic acid selectivities follow the opposite trend [15]. Although there is a large number of catalysts described in the literature and in the patent literature composed of the vanadium oxides systems modified by various promoters, supported on carriers Al_2O_3 , SiO_2 , TiO_2 , and transition metal oxides and favorable for the catalytic gas-phase toluene oxidation to benzaldehyde [17–24], but the toluene conversion is very poor at low temperature (less than 10%). This catalyst system favors the formation of benzoic acid and degradation of carbon dioxide and benzaldehyde selectivity is not very satisfactory. Therefore, a suitable catalyst for the selective production of benzaldehyde from toluene is strongly desired. More attention has been given to the application of the polyoxometalates having Keggin structure, as catalysts for the oxydehydrogenation of alkanes to alkenes [24–27]. Keggin-type polyoxometalates have been widely used as catalysts for one-step conversion of lower alkanes into value-added oxygenated products, such as partial oxidation of methane to methanol [28], oxidation of isobutane to methacrylic acid (MAA) [29], and partial oxidation of propane to acrylic acid (AA) [30]. Molecular oxygen was first proposed to be the oxidizing agent. However, it appeared that use of O_2 (strong oxidant) leads to complete oxidation of hydrocarbons to CO_x . As an alternative to the strong oxidant O_2 , carbon dioxide, the main contributor to the greenhouse effect, was proposed as nontraditional mild oxidant for catalytic oxidation of light alkanes [31–33]. CO_2 utilization as a mild oxidant and an oxygen transfer agent is attracting considerable attention and considered as another route for increasing selectivity and to avoid total oxidation [34]. This approach is expected to open new technology for CO_2 utilization.

In this paper, heteropolyacids $\text{H}_3\text{PMo}_{12}\text{O}_{40}$ (HPMo_{12}) and $\text{H}_4\text{PMo}_{11}\text{VO}_{40}$ (HPMo_{11}V) and heteropolysalts $(\text{NH}_4)_{2.5}\text{Fe}_{0.1}\text{H}_{0.2}\text{PMo}_{12}\text{O}_{40}$ (FePMo_{12}) and $(\text{NH}_4)_4\text{PMo}_{11}(\text{H}_2\text{O})\text{FeO}_{39}$ (PMo_{11}Fe) were prepared, characterized by different methods (FT-IR, UV-visible, MEB, XRD, TGA, and cyclic voltammetry), and the acid/base properties were evaluated using the isopropanol decomposition. The catalytic performance of the catalysts was investigated in partial oxidation of toluene in the temperature range 200°C – 350°C at atmospheric pressure using carbon dioxide as oxidant. The reaction mechanism and kinetics are discussed. The kinetic study was carried over PMo_{11}Fe catalyst at 200°C .

2. Experimental

2.1. Catalyst Preparation. Pure heteropolyacids $\text{H}_3\text{PMo}_{12}\text{O}_{40}$ and $\text{H}_4\text{PMo}_{11}\text{VO}_{40}$ samples were prepared in a classical way [35]. The ammonium-iron salt, $(\text{NH}_4)_{2.5}\text{Fe}_{0.1}\text{H}_{0.2}\text{PMo}_{12}\text{O}_{40}$, was prepared by adding $(\text{NH}_4)_2\text{CO}_3$ solution to an aqueous solution of mixture of $\text{H}_3\text{PMo}_{12}\text{O}_{40}$ and $\text{Fe}(\text{NO}_3)_3$. The precipitate was dried at 50°C under vacuum for 5 h. $(\text{NH}_4)_4\text{PMo}_{11}\text{FeO}_{39}$ salt was prepared by the method described in the literature [36]. The paramolybdate of ammonium was dissolved at 50°C . The mixture of H_3PO_4 , HNO_3 , and $\text{Fe}(\text{NO}_3)_3$ was introduced slowly in the aqueous solution of ammonium paramolybdate at 0°C . Salt of ammonium was precipitated immediately by ammonium nitrates (NH_4NO_3).

2.2. Characterization. Fourier transform infrared spectra (FT-IR) of the heteropolycompounds were obtained in the 400 – 4000 cm^{-1} wavenumber range using a FTIR-8400 Shimadzu spectrometer. UV-vis spectra were recorded on a UV-vis scanning spectrophotometer (Shimadzu UV-2100PC). A 2.5 mM reaction solution of each catalyst was sampled, and the solution was diluted with 400 ml acetonitrile (0.5 mM). Then, the UV-vis spectrum of the solution was measured at 25°C .

The X-ray diffraction (XRD) patterns were obtained on a Siemens “D5000” diffractometer with $\text{Cu K}\alpha$ radiation. The diffractograms were registered at Bragg angle (2θ) = 5 – 45° at a scan rate of $5^\circ/\text{min}$. The thermal decomposition of heteropolycompounds was studied using a Setaram TG-DTA 92. 20 mg of powder was placed in the sample holder, and the temperature was elevated at $5^\circ\text{C}/\text{min}$ in flowing synthetic air.

Isopropanol decomposition and cyclic voltammetry are used to know the information about the redox properties of the heteropolyanions.

The isopropanol decomposition was carried out at atmospheric pressure, in a conventional flow fixed-bed reactor, using 0.2 g of catalyst. Nitrogen was the carrier gas with a flow rate of $50\text{ mL}/\text{min}$. The reaction products were quantified by gas chromatography, using an FID and TC detector.

2.3. Catalytic Tests. Catalytic tests were carried out at atmospheric pressure in a continuous flow fixed-bed tubular glass reactor with 1 g of catalyst pretreated in nitrogen ($2\text{ L}/\text{h}$) for 1 h at the reaction temperature. The carbon dioxide stream ($2\text{ L}/\text{h}$) was saturated with toluene (50 Torr). The oxydehydrogenation (ODH) of toluene was carried out at a relatively lower temperature, 250°C – 350°C , in which the carbon formation is thermodynamically unflavored. The reaction mixture (toluene, benzaldehyde, benzene, benzyl alcohol, methane, and CO) was analyzed by a gas chromatograph (DTC and FID CG, Shimadzu 14B) equipped with columns of Molecular Sieve 5A and Porapak QS.

3. Results and Discussion

3.1. Results of Characterization

3.1.1. FT-IR Analysis. IR spectra of all compounds are given in Figure 1. The characteristic peaks of Keggin unit were observed in the region 1100 – 500 cm^{-1} . According to literature data [37], the origin of the Keggin anion vibration bands, appearing at 1065 , 961 , 864 , and 789 cm^{-1} , is attributed to P-O_a , Mo=O_t , interoctahedral Mo-O_b - Mo , and intraoctahedral Mo-O_c - Mo bands, respectively. The FT-IR spectra presented in Figure 1 showed splitting of P-O_a band of value equal to 40 cm^{-1} for PMo_{11}V and 24 cm^{-1} for PMo_{11}Fe ; the result showed clearly that vanadium and iron ions were introduced into octahedral position. There is no apparent difference between the PMo_{12} and FePMo_{12} spectra; we can note from the results that the primary Keggin structure remains unaltered even when the protons from parental heteropolyacid are substituted by the ammonium and iron cations. The absorption band around 1600 cm^{-1} is indicative of the presence of oxonium ions (H_3O^+) or more

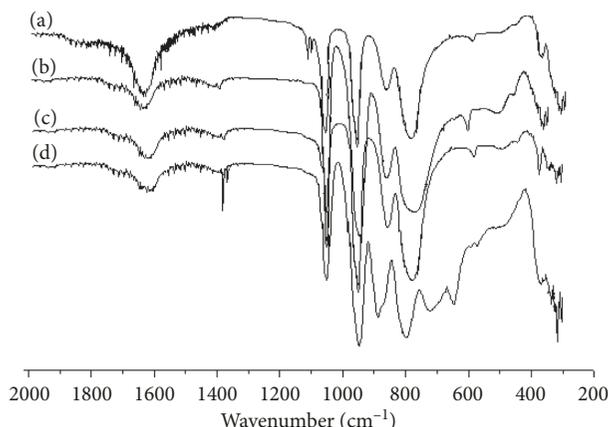


FIGURE 1: FTIR spectra of (a) HPMo_{12} ; (b) FePMo_{12} ; (c) HPMo_{11}V ; (d) PMo_{11}Fe .

likely to dioxonium ions (H_5O_2^+). The band at 1420 cm^{-1} was assigned to N–H stretching.

3.1.2. UV-Visible Analysis. In the near UV, the electronic spectra of Keggin-type polyoxometalates show two absorption bands around 220 nm and 300 nm (Figure 2). These bands attributed to metal oxygen charge transfer. According to the literature [37], these bands are assigned, respectively, to the vibrations of Mo–Ot bonds and Mo–Ob/Oc.

3.1.3. XRD Analysis. As shown in Figure 3, the XRD patterns of $\text{HPMo}_{12}\text{O}_{40}$ and $\text{HPMo}_{11}\text{VO}_{40}$ were substantially similar and have a Keggin-type structure. The acidic $\text{HPMo}_{12}\text{O}_{40}$ and $\text{HPMo}_{11}\text{VO}_{40}$ crystallize in the triclinic system, with $a = 14.10\text{ \AA}$, $b = 14.13\text{ \AA}$, $c = 13.39\text{ \AA}$, $\alpha = 112.1^\circ$, $\beta = 109.8^\circ$, $\gamma = 60.73^\circ$ and $a = 14.04\text{ \AA}$, $b = 10.006\text{ \AA}$, $c = 13.55\text{ \AA}$ and $\alpha = 112^\circ$, $\beta = 109.58^\circ$, $\gamma = 60.72^\circ$, respectively.

The diffraction patterns of FePMo_{12} shown in Figure 3 indicate for the compound the existence of a single crystallographic phase with patterns typical of a cubic phase (intense peak corresponding to [222] plane) (space group $I m\bar{3}$) with $a = b = c = 11.6812$, $Z = 2$.

X-ray analysis of $(\text{NH}_4)_4\text{PMo}_{11}\text{Fe}(\text{H}_2\text{O})\text{O}_{39}\cdot x\text{H}_2\text{O}$ showed that it crystallizes in the monoclinic system, space group $P 2_1/c$, with, $a = 20,07210\text{ \AA}$, $b = 11,55938\text{ \AA}$, $c = 18,77828\text{ \AA}$, $\beta = 95,664^\circ$, and $Z = 2$.

3.1.4. SEM Analysis. The scanning electron micrographs of heteropolycompound catalysts are shown in Figure 4. These images show that the morphology of the particles depends on the heteropolycompound composition and content. The principle structure of FePMo_{12} and PMo_{11}Fe was the same and consisted of rosette-shape plate-like crystals. The particles of HPMo_{12} differ from that of HPMo_{11}V in morphology. The samples of both catalysts contain particles with nonuniform size and shape.

3.1.5. Voltamperometric Analysis. The redox properties of heteropolyanions have been studied by cyclic voltammetry. Keggin anions are able to accept reversibly up to six electrons

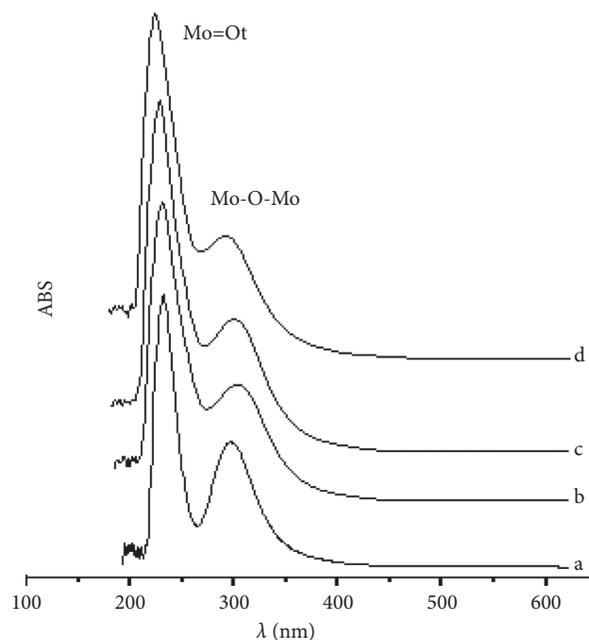


FIGURE 2: UV-visible absorption spectra of (a) PMo_{11}Fe ; (b) FePMo_{12} ; (c) HPMo_{12} ; (d) HPMo_{11}V .

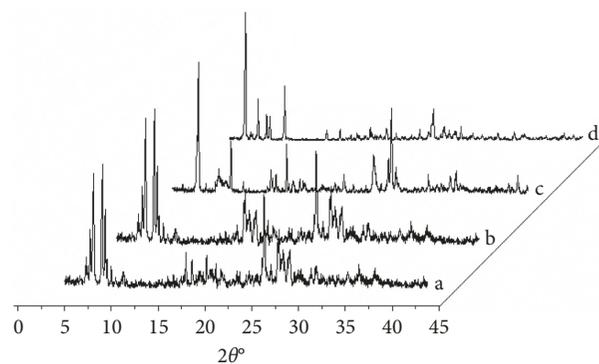


FIGURE 3: XRD patterns of (a) HPMo_{12} ; (b) HPMo_{11}V ; (c) PMo_{11}Fe ; (d) FePMo_{12} .

on the vanadium, molybdenum, or tungsten atoms and thus are potential oxidants. Figure 5(a) shows a cyclic voltammogram of $0.50\text{ mM } [\text{PMo}_{12}\text{O}_{40}]^{3-}$ anion in acetonitrile/water (ratio 1/1 by volume), using a glassy carbon rotating electrode. Three-step, one-electron redox wave was obtained with midpoint potentials, E_{mid} of -0.75 , -0.4 , and -0.05 V assigned to the successive reduction molybdenum centers, where $E_{\text{mid}} = (E_{\text{pc}} - E_{\text{pa}})/2$; E_{pc} and E_{pa} are the cathodic and the anodic peak potentials, respectively. The same result is observed with iron-substituted heteropolymolybdate (FePMo_{12}).

Cyclic Voltammetry studies of HPMo_{11}V and PMo_{11}Fe were particularly informative. Figures 5(c) and 5(d) show typical cyclic voltammograms for the anions $(\text{HPMo}_{11}\text{VO}_{40})^{4-}$ and $(\text{PMo}_{11}\text{FeO}_{39})^{7-}$. The number of redox processes identified and the values of the peak potentials are quite similar. It consists of a reversible one-electron system at -0.11 and -0.7 V for the HPMo_{11}V and for PMo_{11}Fe , respectively, assigned to

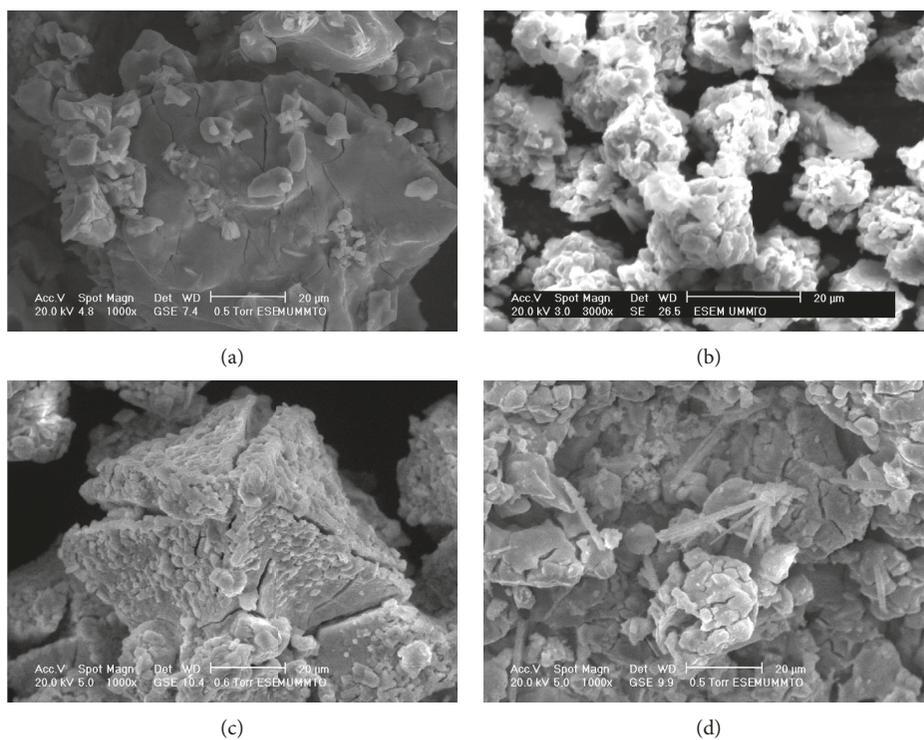


FIGURE 4: Scanning electron micrographs of (a) HPMo₁₂; (b) FePMo₁₂; (c) HPMo₁₁V; (d) PMo₁₁Fe.

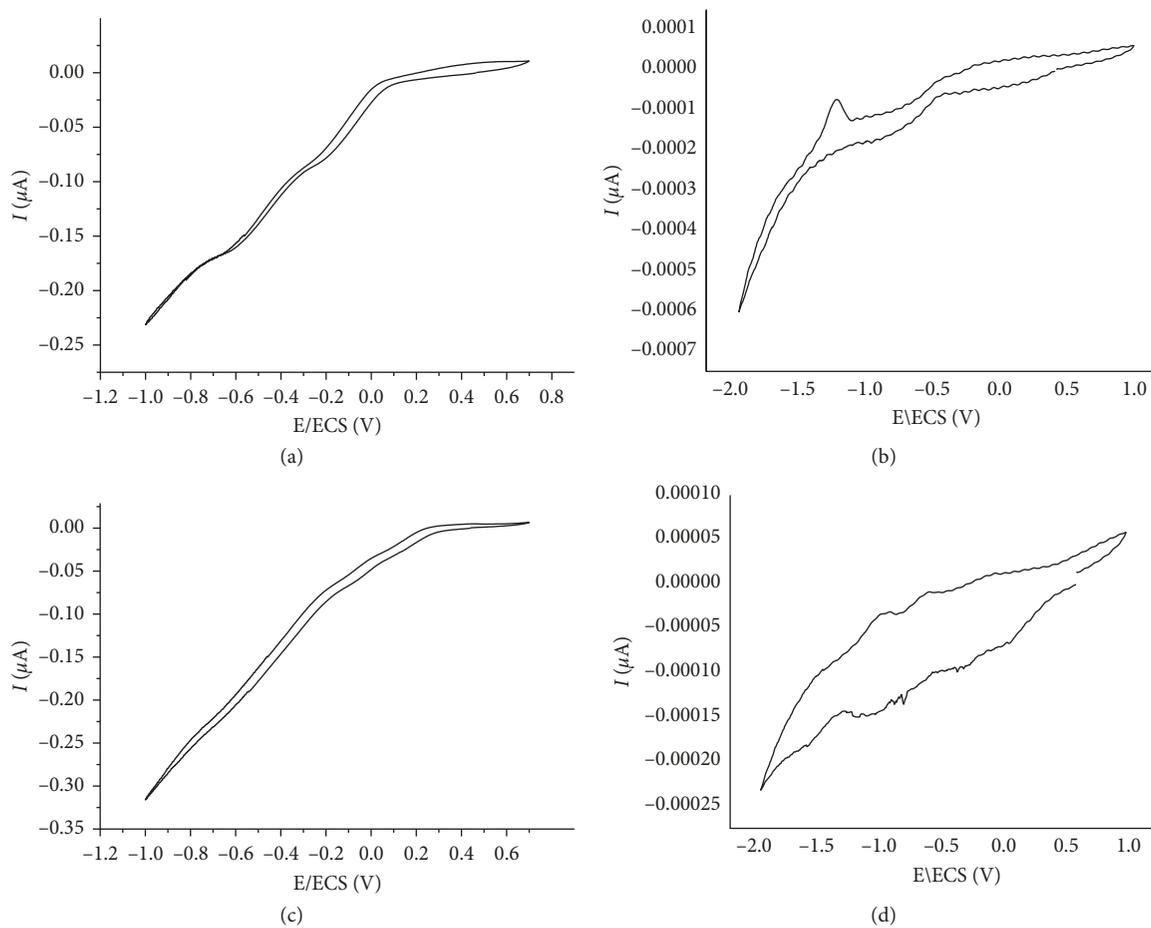


FIGURE 5: Voltamperograms of (a) HPMo₁₂; (b) FePMo₁₂; (c) HPMo₁₁V; (d) PMo₁₁Fe.

the vanadium (V/IV), iron (III/II), and molybdenum (VI/V, V/VI) couples, respectively, and followed by three reversible redox peaks at -0.90 , -1.61 , and -1.8 V for the PMo_{11}V and at -0.85 , -1.68 , and -1.76 for the PMo_{11}Fe . The redox properties of Keggin-type heteropolycompounds can be varied over a wide range by altering the chemical composition. In fact, the electron-accepting properties of Keggin anion are important for oxidative catalysis when electron transfer mechanisms are predominant. In other case, it is the ability of some oxygen atoms of the clusters or the possibility of being involved in complexation reactions that make them good catalysts for oxidation of hydrocarbons.

3.1.6. Thermogravimetric Analysis. The TGA profile for the thermal decomposition of the polyoxometalates is shown in Figure 6. The temperature at which their degradation starts depends on the protonation level and the composition of the polyoxometalates. It can be observed that the weight loss occurred in two steps in case of HPMo_{12} , HPMo_{11}V , and FePMo_{12} samples and three steps in that of PMo_{11}Fe compounds. The first loss at low temperatures ($<120^\circ\text{C}$) corresponds to the liberation of physisorbed water ($12\text{--}13 \text{H}_2\text{O}$), and the second weight loss, between 120°C and 380°C results from the elimination of the three or four acid protons associated with 1.5 or 2 oxygen atoms of the POMs, leading to formation of an anhydride [38].

Their end product of thermal decomposition is the mixture of MoO_3 , P_2O_5 , and V_2O_5 (Scheme (1)), confirmed by X-ray diffraction and IR spectroscopy.

PMo_{11}Fe exhibits high stability (Figure 6). It is known that the decomposition of $(\text{NH}_4)_4\text{PMo}_{11}\text{FeO}_{39}$ begins even at 175°C and involves three stages in the process of transformation of $(\text{NH}_4)_4\text{PMo}_{11}\text{FeO}_{39}$ into mixture oxides P_2O_5 , MoO_3 , and Fe_2O_3 (Scheme 2), located at approximately 150°C , 280°C , and 450°C . The first peak is associated with removal of water from the polyoxometalate. The main decomposition peak at 250°C corresponds to the loss of constitution water. The third peak may be related to the decomposition of ammonium cations to ammonia and can be explained as shown.

3.1.7. Acidic Properties of Polyoxometalates. The gas-phase decomposition of isopropanol is an important probe reaction, as its product selectivity depends on the surface concentration of redox, basic, and acidic sites [39]. Redox sites or strong basic sites produce propanone by dehydrogenation reaction (a), whereas acidic sites give rise to propene and di-isopropylether, respectively [40], by dehydration reaction (b) (Figure 7).

The results obtained from the isopropanol decomposition using POMs as catalysts as a function of reaction temperature are presented in Table 1.

It is clear that HPMo_{11}V and HPMo_{12} , are the most active catalysts. The high activity can be correlated with increasing the surface acidity associated with the presence of protons in Keggin structure. Propene is the major reaction product. However, it is also observed that, when the protons in the parent acids ($\text{H}_3\text{PMo}_{12}\text{O}_{40}$) are partially exchanged by iron

and ammonium cations, $[(\text{NH}_4)_{2.5}\text{Fe}_{0.1}\text{H}_{0.2}\text{PMo}_{12}\text{O}_{40}]$ improves the catalytic activity (Table 1). This can be attributed to the partial hydrolysis of the polyanion during preparation, which formed weakly acidic H^+ . On the contrary, when the iron is in anionic position (PMo_{11}Fe), the initial activity decreased, resulting in conversion relatively lower than the iron in cationic position (FePMo_{12}). This decrease attributed to the decrease in the number and the strength of the acid sites of the catalyst. The presence of redox species $\text{Mo}^{\text{VI}}/\text{Mo}^{\text{IV}}$, $\text{V}^{\text{V}}/\text{V}^{\text{IV}}$, and $\text{Fe}^{\text{III}}/\text{Fe}^{\text{II}}$ in the catalysts can contribute to dehydration and dehydrogenation in the decomposition of isopropanol.

3.2. Catalytic Test

3.2.1. Catalytic Activity. The effect of reaction temperature for the partial oxidation of toluene over polyoxometalates was estimated at 250°C , 300°C , and 350°C . The toluene conversion and the product selectivity in a CO_2 atmosphere at time on stream of 8 h are shown in Table 2. The toluene conversion increased with increasing temperature for all catalysts. However, high temperatures also enhance an undesired parallel process, dealkylation reaction (benzene and methane) that reduces the selectivity to the desired product (benzyl alcohol or benzaldehyde).

In the reaction with the $\text{H}_3\text{PMo}_{12}\text{O}_{40}$ catalyst, the toluene conversion increased from 7 to 52.3% with an increase in the reaction temperature from 250°C to 350°C . The benzaldehyde selectivity decreased from 63% at 250°C to 36.0% at 350°C , that of benzene (dealkylation product) increased from 37% to 64%. Hence, higher temperatures cause higher dealkylation of toluene and formation of lower amounts of benzaldehyde. At all temperatures, HPMo_{11}V displayed very similar conversion than HPMo_{12} but is more selective towards benzaldehyde (80–67% selectivity) benzyl alcohol was also observed as a minor product. These results are in accord with those obtained by other authors which have demonstrated that the use of vanadium-containing polyoxometalates improved catalytic performances (conversion and selectivity) as in the case of isobutane oxidation [29, 41]. On the other hand, it was reported that both V^{5+} and V^{4+} species were likely the active sites in the selective oxidation of toluene to benzaldehyde [42]. In the case of $\text{H}_4\text{PMo}_{11}\text{VO}_{40}$, the reduction of V^{5+} to V^{4+} is very quick leading to stability of benzaldehyde selectivity from the beginning of the reaction. This agrees with the obtained results by Cavani et al., in oxidative isobutane [43]; the presence of vanadium will accelerate the reduction of compound suggesting that V^{4+} species act as reducing species towards Mo^{6+} leading to Mo^{5+} and V^{5+} species. In the reaction with the FePMo_{12} catalyst (Table 2), toluene conversion is similar to that of the HPMo_{12} catalyst observed. The benzaldehyde selectivity at the reaction temperature of 250°C is below 40%, which has been decreased to approximately 30% and 21% with an increase in the reaction temperature from 250°C to 300°C and 350°C , respectively. However, the benzyl alcohol selectivity remained constant in the range between 250°C and 350°C . Higher benzene selectivity is observed at all

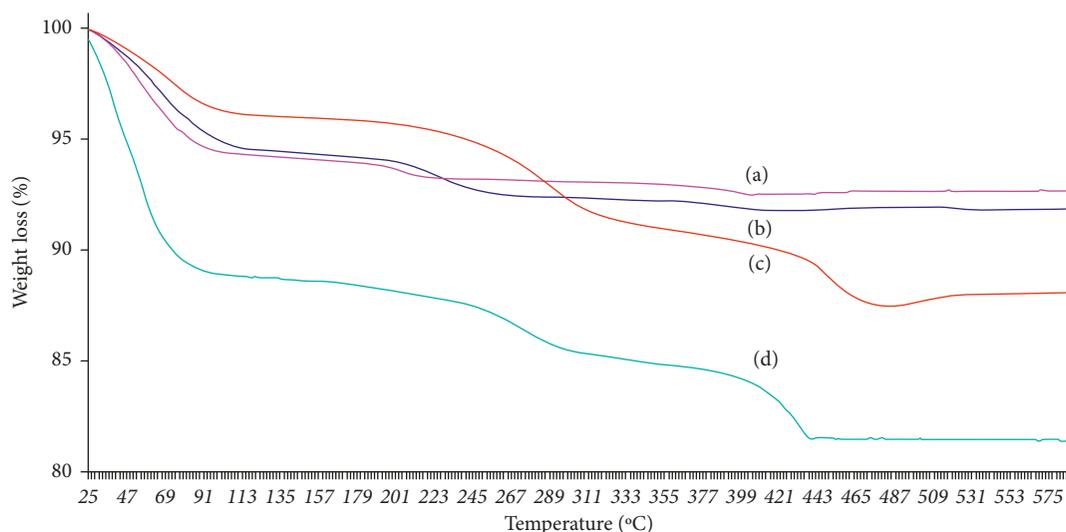
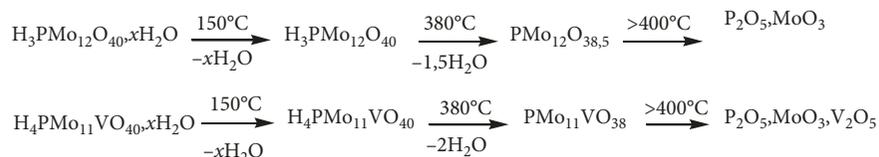
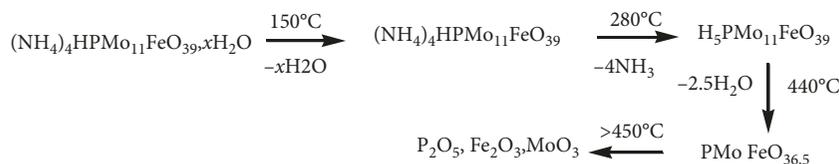


FIGURE 6: The TGA profiles of (a) HPMo_{12} ; (b) HPMo_{11}V ; (c) FePMo_{11} ; (d) PMo_{11}Fe .



SCHEME 1: Thermal decomposition process of HPMo_{12} and HPMo_{11}V .



SCHEME 2: Thermal decomposition process of PMo_{11}Fe .

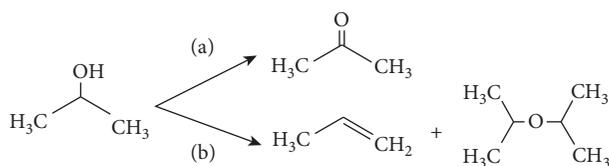


FIGURE 7: Isopropanol decomposition on acid and redox sites.

reaction temperatures. The obtained results indicated that the selectivity of benzene increases with increasing temperature; thus, FePMo_{12} surface has strong acidic sites, which is evident from the higher dealkylation process than dehydrogenation; these results agree with those observed in dehydrogenation of isopropanol to propene. The same products (benzyl alcohol, benzaldehyde, and benzene) are obtained with PMo_{11}Fe , and the results are listed in Table 2. Generally, the conversion of toluene into oxidized products was much more efficient than for the catalysts listed in Table 2. With PMo_{11}Fe , conversion of toluene is more important and becomes highly selective to the formation of benzyl alcohol at low temperatures. The catalyst

also gave benzene but only as a minor product, benzaldehyde being the major one. This is suggested that iron in anionic position decreases the acidity and accelerates more the redox process. The results for PMo_{11}Fe show that the conversion of toluene to oxygenate products (benzyl alcohol + benzaldehyde) is higher than the dealkylation process (benzene) indicating the redox of PMo_{11}Fe surface. The easy redox cycle between oxidized and reduced iron species ($\text{Fe}^{3+}/\text{Fe}^{2+}$) generates a highly active catalyst.

3.2.2. Reaction Kinetics. A kinetic study of toluene partial oxidation was performed at 200°C over PMo_{11}Fe , with a total flow rate of 50 ml/min and catalyst weight of 200 mg. The reaction rate of toluene oxidation by carbon dioxide was given by

$$r = kP^{\alpha}\text{toluene} P^{\beta}\text{CO}_2, \quad (1)$$

where α and β are the partial order of toluene and carbon dioxide.

TABLE 1: Catalytic activity of catalysts at different temperatures in isopropanol decomposition.

Catalysts	T (°C)	Conversion (%)	Products selectivities (%)		
			Propylene	Di-isopropylether	Acetone
H ₃ PMo ₁₂ O ₄₀	100	17	60	30	10
	150	60	80	13	7
	200	90	92	4	4
H ₄ PMo ₁₁ VO ₄₀	100	19	56	16	28
	150	65	84	6	10
	200	97	90	2	8
FePMo ₁₂ O ₄₀	100	10	72	20	8
	150	80	90	9	1
	200	95	98	1	1
PMo ₁₁ FeO ₃₉	100	5	15	5	80
	150	32	35	3	62
	200	45	69	1	30

TABLE 2: Effect of reaction temperature on the partial oxidation of toluene with CO₂ over polyoxometalates.

Catalysts	T (°C)	Conversion (%)	Products' selectivity (%)		
			C ₆ H ₆	C ₆ H ₅ -CH ₂ OH	C ₆ H ₅ -CHO
H ₃ PMo ₁₂ O ₄₀	250	7	37	—	63
	300	14.5	51	—	49
	350	52.3	64	—	36
H ₄ PMo ₁₁ VO ₄₀	250	6.1	12	8	80
	300	16.4	18	10	72
	350	54.7	31	2	67
PMo ₁₁ Fe	200	5	30	65	5
	250	26	25	50	25
	300	44.4	20	32	48
	350	75.4	19	15	66
FePMo ₁₂	250	14	39	21	40
	300	31.0	51	19	30
	350	55.1	61	18	21

The value of these orders can then be obtained by linearizing this equation and by plotting the corresponding logarithmic curves:

$$\ln r = \ln k + \alpha \ln(P_{\text{toluene}}) + \beta \ln(P_{\text{CO}_2}). \quad (2)$$

In most cases, a constant carbon dioxide pressure of 50 Torr was used in the first set of experiments as the pressure of the toluene was varied from 2.5 to 25 Torr (Figure 8(a)), and the Ph-CH₃ pressure was fixed at 5 Torr while the CO₂ pressure was changed from 50 to 100 Torr in the second (Figure 8(b)).

The results indicated a reaction of zero order with respect to carbon dioxide and first order with respect to toluene.

These orders suggested the reaction was of the Mars and van Krevelen type, with the rate-determining step being the reduction of the catalyst surface by the hydrocarbon [44].

According to the Mars and van Krevelen model, the reaction of toluene partial oxidation occurs in two steps: the oxidation of toluene by the oxidized catalyst (3) and the reoxidation of reduced catalyst (4).



In these equations SO, S, $k_{(\text{red})}$, and $k_{(\text{ox})}$, respectively, represent the oxidized and reduced sites of the catalysts, the rate constants of the reduction, and oxidation stages of the catalyst. The rate of steps (3) and (4) would then be

$$\begin{aligned} r(\text{red}) &= k_{(\text{red})} P_{\text{toluene}} [\text{SO}] \\ r(\text{ox}) &= k_{(\text{ox})} P_{\text{CO}_2} [\text{S}] \end{aligned} \quad (5)$$

In steady state, these rates are equal: $r = r(\text{red}) = r(\text{ox})$.

Moreover, the material balance corresponding to the reaction sites is $[\text{SO}] + [\text{S}] = [\text{S}]_0$; $[\text{SO}]$, $[\text{S}]$, and $[\text{S}]_0$ are, respectively, the concentrations of the oxidized, reduced, and total sites. The resolution of the system of equations above makes it possible to obtain the expression of the rate of reaction in steady state:

$$r = \frac{k_{(\text{red})} P_{\text{toluene}} \times k_{(\text{ox})} P_{\text{CO}_2}^n}{k_{(\text{red})} P_{\text{toluene}} + k_{(\text{ox})} P_{\text{CO}_2}^n} \times [\text{S}]_0. \quad (6)$$

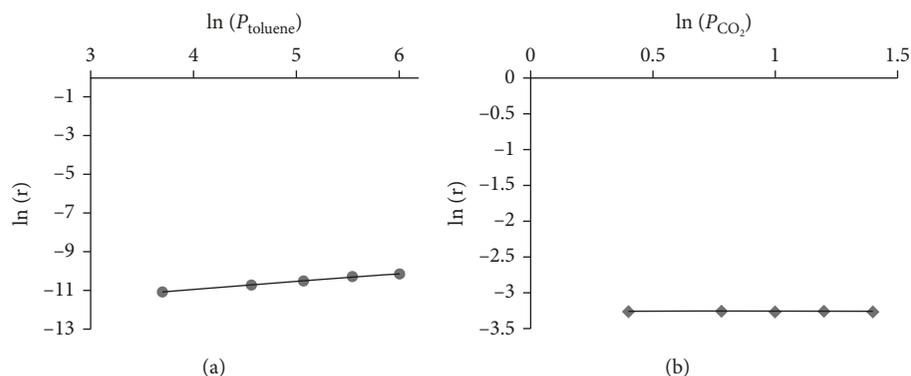


FIGURE 8: Reaction order of partial oxidation of toluene by carbon dioxide.

If $[S]_0 = 1$:

$$r = \frac{k_{(\text{red})}P_{\text{toluene}} \times k_{(\text{ox})}P_{\text{CO}_2}^n}{k_{(\text{red})}P_{\text{toluene}} + k_{(\text{ox})}P_{\text{CO}_2}^n} \quad (7)$$

If the reduction step is limiting, it is possible to write $k_{(\text{ox})} \gg k_{(\text{red})} P_{\text{CO}_2}$.

Hence, $r \cong k_{(\text{red})} P_{\text{toluene}} = k P_{\text{toluene}}$, where k is the rate constant of the global process. The kinetics is indeed of the first order with respect to the toluene.

Moreover, the values of the rate constants of the reduction and reoxidation steps were determined graphically by linearizing the equation of the overall rate:

$$\frac{1}{r} = \frac{1}{k} (\text{red})P_{\text{toluene}} + \frac{1}{k} (\text{ox})P_{\text{CO}_2} \quad (8)$$

The plotting of the corresponding curves at constant pressure of toluene or carbon dioxide leads to the following values: $k_{(\text{red})} = 4,1 \cdot 10^{-4} \text{ mol} \cdot \text{min}^{-1} \cdot \text{g}^{-1} \cdot \text{Torr}^{-1}$ and $k_{(\text{ox})} = 0,50 \text{ mol} \cdot \text{min}^{-1} \cdot \text{g}^{-1} \cdot \text{Torr}^{-1}$. This conclusion was in good agreement with the decomposition of isopropanol (Table 2) and cyclic voltammetry studies showing the redox properties of the PMo_{11}Fe catalyst. Since $k_{(\text{red})} \ll k_{(\text{ox})}$, the limiting step of the reaction is the reoxidation of the catalyst as found by Van Der Wiele et al. [21]. In initial kinetic conditions, only benzyl alcohol and benzaldehyde as oxygenate products were detected. Besides, when the contact time tended to zero, the $\text{C}_6\text{H}_5\text{-CH}_3\text{OH}/\text{C}_6\text{H}_5\text{-CHO}$ (γ) or $\text{C}_6\text{H}_5\text{-CHO}/\text{C}_6\text{H}_5\text{-CH}_3\text{OH}$ ($1/\gamma$) ratios tended towards zero or an infinite value, respectively (Figure 9). These trends suggested that benzyl alcohol was an intermediate in benzaldehyde formation, as shown by the following reaction pathway:



The same trend was observed during the study of the effect of the reaction temperature on the product selectivities.

Figure 10 shows that selectivity of benzyl alcohol decreases as the temperature increases, while benzaldehyde selectivity increases with reaction temperature. This result confirmed that benzyl alcohol was a precursor in benzaldehyde formation.

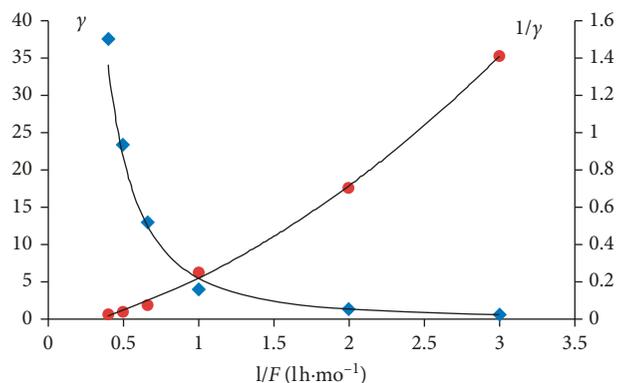


FIGURE 9: Effect of the contact time on the relative selectivities in the partial oxidation of toluene at 200°C over PMo_{11}Fe .

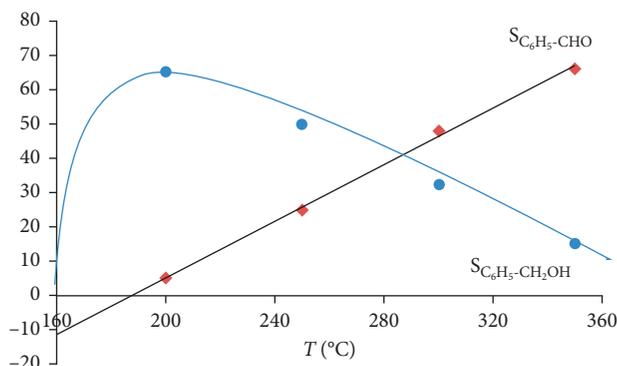


FIGURE 10: Effect of the reaction temperature on the selectivities in the partial oxidation of toluene over PMo_{11}Fe .

Activation energy of the catalytic oxidation of toluene to benzaldehyde, using CO_2 as oxidant, was determined from the plot of $\ln k$ against $1/T$ (Figure 11). The activation energy was calculated using the following equation: $\text{slope} = -E_a/R$, where E_a is activation energy, R is the gas constant. The value of activation energy was found to be 62.639 KJ/mol.

3.2.3. Mechanism and Pathway of Toluene Partial Oxidation by CO_2 . It has been well recognized that the selective

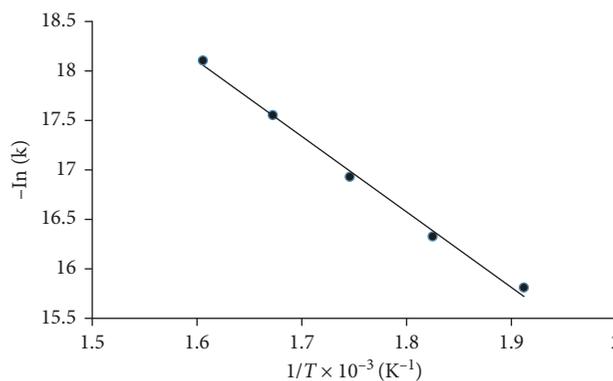


FIGURE 11: Arrhenius plot for determination of activation energy.

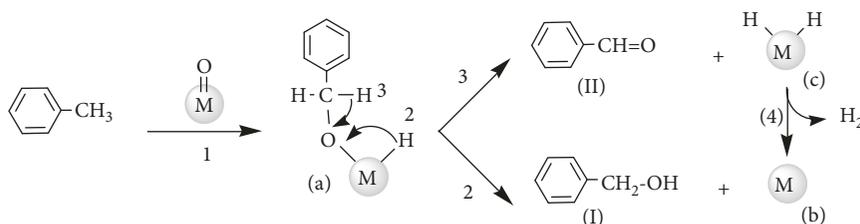


FIGURE 12: Proposed mechanism for the partial oxidation of toluene on M=O centers.

oxidation of toluene proceeded via a van Krevelen redox mechanism [44], but the pathways and product distribution depended on the nature of catalysts and the reaction conditions. For toluene partial oxidation to benzyl alcohol and benzaldehyde using carbon dioxide as oxidant, the most strongly supported mechanism consists of a consecutive conversion scheme $C_6H_5-CH_3 \rightarrow C_6H_5-CH_2OH \rightarrow C_6H_5-CHO$. This indicates that benzyl alcohol can be formed as a precursor of benzaldehyde in the catalytic oxidation of toluene over a transition metallic oxide catalyst. According to the widely accepted mechanism of partial oxidation of toluene by CO_2 , the breaking of the C–H bond in the toluene is the rate-determining step [45]. In the case of the catalytic partial oxidation of toluene by CO_2 over polyoxometalate catalysts, the formation of benzaldehyde and benzyl alcohol during the toluene adsorption suggests that toluene is activated by abstracting a hydrogen atom from the methyl group. This is followed by the bonding of the lattice oxygen nearby over the M=O centers with the primary carbon of benzyl species leading to the formation of benzyloxy species (a). This is in agreement with the work of Busca et al. [46]. They studied by IR spectroscopy the interaction of light hydrocarbons over the $MgCr_2O_4$. It has been concluded that every hydrocarbon reacts at its weakest C–H bond giving rise to the corresponding alkoxide species. In the first step of the mechanism, $C_6H_5-CH_3$ adsorbed on the M=O centers to form an benzyloxy species ($C_6H_5-CH_2-O-M-H$) (a) (Step 1). Benzyl alcohol (I) is then formed via the transfer of a hydrogen atom from the hybrid group to the benzyloxy (Step 2). Surface benzyloxy groups decompose to the adsorbed C_6H_5-CHO ; desorption of benzaldehyde (II) and dihydrogen lead to the final products and a reduced catalyst surface (Step 3). The pathway for the oxidation of toluene over polyoxometalates is shown in the reaction scheme Figure 12.

Reoxidation of the catalyst by CO_2 restores the lattice oxygen atom of the M metal, then the M=O centers are reestablished for the next turnover cycle. This sequence is represented by (Figure 13)

Toluene, when passed over different heteropolycompound catalysts at $250^\circ C-400^\circ C$, has been found to yield benzyl alcohol and benzaldehyde in addition to the hydrodealkylation [47] products benzene (III) and methane (IV). Here, the toluene reacts with the adsorbed hydrogen to produce benzene and methane as shown in Figure 14.

4. Conclusion

Both IR spectroscopy and X-ray diffraction indicate for $FePMo_{12}$ and $PMo_{11}Fe$ salts, the presence of a single crystalline phase, and IR spectra typical of the Keggin anion; TGA shows that the salts containing iron are more stable than the pure acidic $H_3PMo_{12}O_{40}$ and $H_4PMo_{11}VO_{40}$. These results show also that the vanadium and iron play a very important role in benzaldehyde selectivity and indicate clearly that the substitution of protons by NH_4^+ and Fe^{3+} cations or Mo^{6+} by V^{5+} and Fe^{3+} induced important changes in the acid-base and oxidoreduction properties of phosphomolybdate heteropolyanions of Keggin structure. In this study, $PMo_{11}V$ and $PMo_{11}Fe$ catalyzed the toluene partial oxidation with carbon dioxide as an oxidant to the corresponding oxygenate compounds efficiently and selectively.

The partial oxidation of toluene selectively produced oxygenated compounds besides benzene. The reaction orders were 1 and 0 in toluene and carbon dioxide, respectively. The overall process seemed to obey a redox mechanism of Mars and van Krevelen type, in which the reduction step would be rate determining. Benzyl alcohol

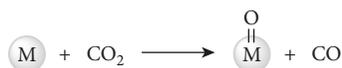


FIGURE 13



FIGURE 14: Toluene hydrodealkylation.

appeared as the reaction intermediate in benzaldehyde formation.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Supplementary Materials

The supplementary materials for this work contain the detailed method of preparation of pure acids $\text{H}_3\text{PMo}_{12}\text{O}_{40}$ and $\text{H}_4\text{PMo}_{11}\text{VO}_{40}$ and heteropolysalts $(\text{NH}_4)_{2.5}\text{Fe}_{0.08}\text{H}_{0.26}\text{PMo}_{12}\text{O}_{40}$ and $(\text{NH}_4)_4\text{PMo}_{11}(\text{H}_2\text{O})\text{FeO}_{39}$ with iron outside and inside Keggin structure, respectively. The supplementary materials include the expressions of toluene conversion and products' selectivities. (*Supplementary Materials*)

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