

Synthesis and characterization of vanadium pentoxide on different metal oxides by the sol-gel process for application in the conversion of the SO₂ to SO₃

N. Badri ^a, Y. Chhiti ^b, F. Bentiss ^a, M. Bensitel ^{a*}

^a Laboratory of Catalysis and Corrosion of Materials (LCCM), Faculty of Sciences, Chouaib Doukkali University, PO Box 20, M-24000 El Jadida, Morocco

^b Ecole Nationale Supérieure de Chimie, Ibn Tofail University, Kénitra, Morocco

Abstract

Sulfuric acid is the largest volume chemical currently produced in the world. Is manufactured by the contact process, it involves three stages: combustion, conversion and absorption. The SO₂ conversion reaction is the key step in the process, it uses catalysis. The objective of this work is to synthesize a series of mixed vanadium oxides X% / MO₂ with M (Si, Al and Ti) by sol-gel process followed by calcination at 400 ° C, in order to study their reactivity in the catalytic oxidation of SO₂ to SO₃. Characterization of those materials was carried out by Fourier transform infrared (FT-IR) spectroscopy, scanning electron microscopy (SEM) with energy dispersive X-ray (EDX), X-ray diffraction, thermal analysis (TDA/TGA) and N₂ adsorption at 77 K. Their acid-base properties are studied by the decomposition reaction of isopropanol (propan-2-ol). In this work, we have studied the reactivity of the catalysts prepared in the conversion of SO₂ to SO₃ by an iodometric as dosage which consists in assaying the iode with sodium thiosulfate.

* Corresponding author:

mbensitel@yahoo.fr

Tel: +212 6 72 79 37 42

Received 23 March 2020,

Revised 20 April 2020,

Accepted 05 May 2020.

Keywords: Mixed oxide; Vanadium; Sol-gel; Reactivity; Catalytic conversion; SO₂; SO₃; Iodometric.

1. Introduction

Sulfuric acid, also called vitriol oil or vitriol, is a toxic chemical compound of formula H_2SO_4 , miscible with water in all proportions. It is an industrial product of primary importance and finds many applications; its industrial preparation is done by two processes: lead chamber process and contact process. The "lead chamber" process, introduced in 1746 to manufacture the acid necessary for the bleaching of textiles, the first chambers had a capacity of production of about 50 kg of acid titrating 33% in mass, in 1827, Gay Lussac introduced a method of absorption of nitrogen oxides, which allowed the implementation of a continuous process of manufacture [1]. The sulfuric acid manufacturing process used in Morocco phosphorus Jorf Lasfar is a double absorption process. It involves three stages: the combustion of sulfur, the conversion of SO_2 and the absorption of SO_3 to form a solution containing 98 to 99% sulfuric acid H_2SO_4 [2]. The reaction to convert SO_2 to SO_3 is the key step in the process. Its activation energy is very high for this the speed is very slow and therefore gives a low conversion rate. To lower the energy barrier, catalysts are used. This reaction is limited. It is carried out in a multi-stage reactor called a converter, equipped with several successive catalyst beds. The latter is formed of a silica support (SiO_2) having a very large specific surface on which is deposited the active phase generally of vanadium pentoxide (V_2O_5) [3]. Industrially, the catalyst operates in an adiabatic fixed bed. The reaction being balanced in the field of activity of the catalyst, this requires the use of several catalytic layers with intermediate cooling of the gases (either by exchanger, or by injection of fresh air). Operating temperatures vary from 400 to 650°C. The design of catalysts is very important in industrial synthesis. So the new trend is towards the use of heterogeneous catalysts in industrial processes. This is why we need to prepare efficient catalysts that meet certain criteria such as: selectivity, stability, activity. Transition metal catalysts are the most used in oxidation reactions, among these metals, vanadium which is widely used in catalysis as a metal oxide, due to the restriction of thermal stability and mechanical strength of vanadium oxides, most catalysts based on vanadium oxides consist of a phase of vanadium oxide deposited on the surface of a support. Several studies show that vanadium V^{5+} is the active site responsible for the oxidation reaction of SO_2 to SO_3 . The supports generally used are: CeO_2 , ZrO_2 , TiO_2 ... Attention in this study is to prepare a series of vanadium mixed oxide $\text{X}\% / \text{MO}_2$ with M (Si, Al and Ti) by sol-gel process, in order to study their reactivity in SO_2 catalytic conversion to SO_3 by an iodometric dosage test.

2. Materials and methods

2.1. Materials and Chemicals

The three supports materials were synthesized by sol-gel. Table 1 brings together the characteristics of the precursors used in the preparation.

Table 1: Characteristics of the precursors.

Materials	precursor	Chemical formula	M (g/mol)	Cas-NR	purity
TiO_2	titanium isopropoxide	$\text{Ti}(\text{O}-\text{C}_4\text{H}_9)_4$	284.22	546-68-9	97%
Al_2O_3	Aluminum isopropoxide	$\text{Al}[(\text{CH}_3)_2\text{CHO}]_3$ (AIP)	204.25	555-31-7	99%
SiO_2	tetraethylorthosilicate	$\text{Si}(\text{OC}_2\text{H}_5)_4$ (TEOS)	208,3275	78-10-4	98%
V_2O_5	Ammonium metavanadate	$\text{NH}_4(\text{VO}_3)$	116,98	7803-55-6	99%

2.2. Catalyst preparation

In this work, TiO_2 , Al_2O_3 and SiO_2 were used as catalyst support materials. The sol-gel preparation procedure used in this case involves three steps: gel preparation, drying and calcination. TiO_2 gel synthesis was started by mixing titanium isopropoxide ($\text{Ti}(\text{OC}_4\text{H}_9)_4$, Sigma Aldrich, 97%) with isopropanol, the mixture is stirred magnetically at room temperature for 1 h followed by the addition of HCl in order to catalyse the condensation process. After this, the solution was hydrolysed with ultrapure water. At the end of water addition, a white gel was obtained. The molar ratio of $\text{Ti}(\text{O}-\text{C}_4\text{H}_9)_4/\text{C}_3\text{H}_8\text{O}/\text{HCl}/\text{H}_2\text{O}$ was 1/15/0.3/4. Then, the sol was dried in a sand bath at 60°C for 24 h and then in the oven at 120°C overnight and calcined at 400°C for 4 hours [4]. The SiO_2 support was prepared from $\text{Si}(\text{OC}_2\text{H}_5)_4$ precursors using a sol-gel method, the mixture of 16.8 mL of TEOS and 13.24 mL of ethanol or 14 mL of propanol and 4 mL of HNO_3 (2.5 mol L^{-1}) were kept under stirred overnight. The gel formed is dried in a sand bath at 60°C for 24 h and then in the oven at 120°C overnight and finally calcined at 400°C for 4 hours [5]. Aluminum isopropoxide (AIP) has been used as a precursor for alumina, acetic acid as a hydrolysis rate regulator and isopropanol as a solvent. The molar ratios of the reagents AIP: Solvent, AIP: H_2O and AIP: AA were 1: 60, 1: 1 and 40: 1, the mixture AIP and isopropanol is stirred magnetically at room temperature for 3 hours until all the solutions are dissolved. Then, the mixture of 0.23 mL of acetic acid and 10 mL of distilled water was added drop wise to the above solution. The solution was stirred magnetically for 3h to complete the hydrolysis. At all times, the reaction solution was stirred at 150 rpm to form a uniform product. The final solution was placed in a glass container at room temperature for 24 hours to form gel. Finally, the gel was dried in an oven at 120°C for 6 h and then calcined at 400°C for 4 hours with a ramp rate of $5^\circ\text{C} / \text{min}$ [6]. Ammonium metavanadate has been used as active phase precursors. After dissolving the precursors with ultrapure water and introducing the support material, stirring was continued at room temperature overnight. Then, the sample was dried at 80°C using a sand bath. Finally, the catalyst samples were calcined in air at 450°C for 4 h [7]. The various mixed oxides are of the $\text{V}_2\text{O}_5/\text{TiO}_2$, $\text{V}_2\text{O}_5/\text{SiO}_2$ and $\text{V}_2\text{O}_5/\text{Al}_2\text{O}_3$ type with 5% vanadium content. The flowchart below summarizes the preparation of the three catalysts:

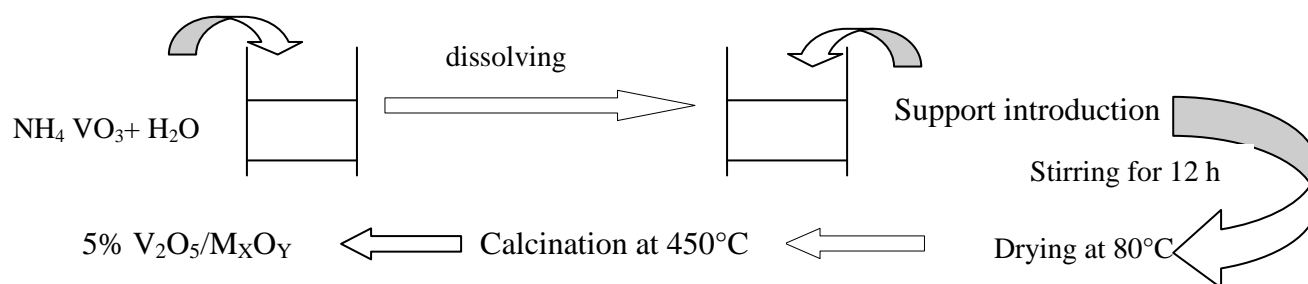


Figure 1: Flowchart of the catalyst preparation method.

2.3. Catalysts characterization

Thermogravimetric analysis of supports was analyzed in the range 25°C - 1200°C with the heating rate $10^\circ\text{C}/\text{min}$ at air atmosphere, recorded using thermo-gram Shimadzu D60. Catalysts were characterized by X-ray diffraction (XRD) analysis using a Bruker-eco D8 Advance diffractometer with Cu-K_α radiation source ($\lambda = 1.5418 \text{ \AA}$). Chemical characterization of catalysts was carried out by FT-IR spectroscopy in order to identify the functional groups at the surface of carbon materials. The infrared transmission spectra were recorded with a Nicolet, Impact 400 D spectrometer, from 500 to 4000 cm^{-1} . Morphological characterizations of the samples were performed using Scanning Electron Microscopy (SEM) Hitachi S-3400N. The specific areas of the supports were determined by the conventional BET method.

2.3. Catalysts testing

2.3.1. decomposition reaction of isopropanol

The acid-base properties of the oxides were determined by the decomposition reaction of isopropanol (propan-2-ol, Aldrich 99.99%). The products obtained are: acetone and / or propene. To explain how the dehydration reaction occurs, all the mechanisms described in the bibliography involve an acid attack on alcoholic oxygen followed by a transfer of hydrogen to a basic site. In the first step, the isopropanol behaves like a base with respect to the surface, and then the resulting intermediate form behaves like an acid in the second step. Propene formation requires a balance between the acid sites and the basic sites of the oxide. The mechanism (Fig. 2) suggests the formation of propene on a Brönsted acid surface or on a Lewis acid site.

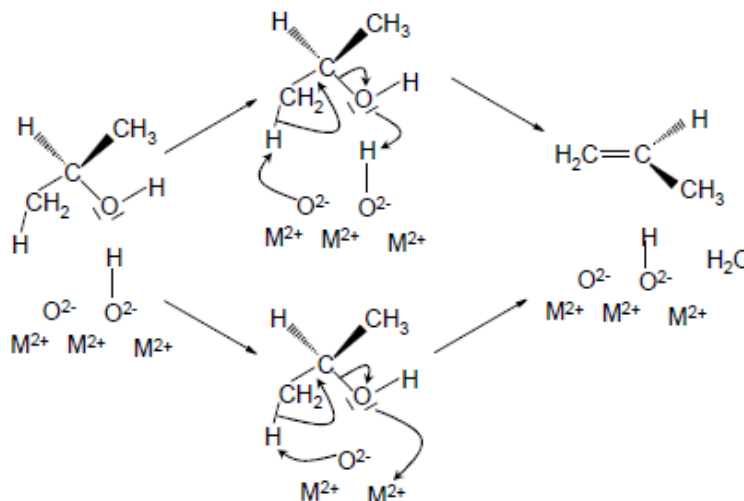


Figure 2: Dehydration of isopropanol: acid-base model [8].

For the dehydrogenation reaction, the oxides which produce acetone have high basicity values in the Parks scale [9]. It can therefore be assumed that the alcohol will first behave as an acid vis-à-vis these surfaces and lose the alcoholic hydrogen at the time of adsorption. The formation of acetone from the adsorbed alkoxy form requires the loss of a hydride ion, therefore the participation of an acid center. In accordance with the generally accepted hypotheses, a ‘basic’ surface would therefore favor dehydrogenation [10]. The mechanism (Figure 3) suggests the formation of acetone on oxygen.

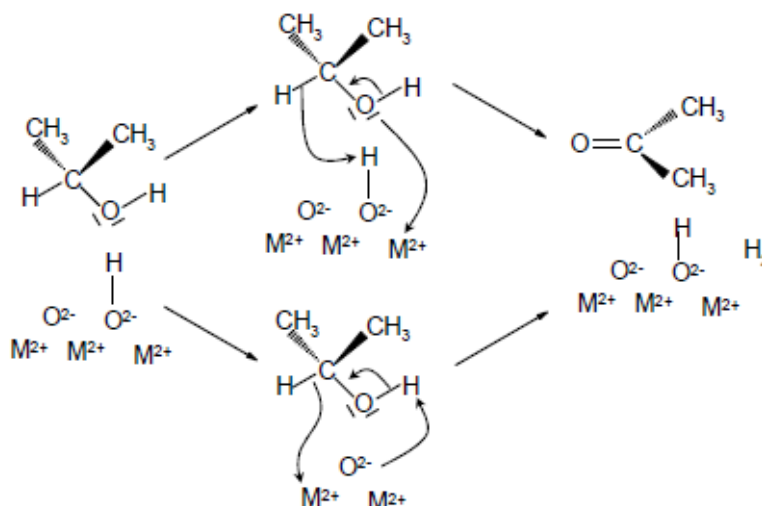


Figure 3: Acetone formation: “acid-base” model [8].

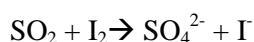
The reaction was conducted between 220°C and 300°C in a fixed bed Pyrex glass reactor, using 100 mg of catalyst. The oxides undergo a neutral pretreatment under nitrogen flow. The tests were carried out at atmospheric pressure and the saturated vapor of the gaseous propane-2-ol reagent is obtained by bubbling nitrogen into the liquid propan-2-ol placed in a saturator immersed in an ice bath. The catalytic test it includes:

- ❖ air and nitrogen gas reserve equipped with a pressure reducer and massive flow control valves,
- ❖ thermostatic saturator containing the liquid reagent,
- ❖ two-by pass liquid system reagent allowing the in situ pretreatment of the sample and the injection of 2-propanol before it passes over the catalytic bed;
- ❖ reactor containing the catalyst placed in a furnace whose temperature is adjusted by a programmer.

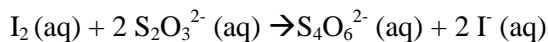
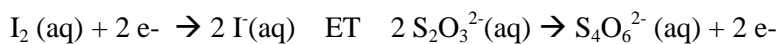
The quantities measured from the chromatograms are the areas of unreacted 2-propanol and those of propene.

2.3.2. Iodometric dosage

To determine the amount of unconverted SO₂ and subsequently the conversion, iodometric and back titration was used. The bubbler at the outlet contains a solution of iodine which reacts with unconverted SO₂ according to the reaction:



The excess of the solution of I₂ is dosed back by a solution of thiosulphate according to the reactions:



SO₂ gas which has not reacted with O₂ can then be calculated as follows:

$$n(\text{SO}_2)_{\text{unreacted}} = \text{initial } n(\text{I}_2) - n(\text{I}_2)_{\text{measured by Na}_2\text{S}_2\text{O}_3}$$

Operating condition:

- ❖ flow of SO₂ / N₂ = 133 ml / min
- ❖ flow rate of O₂ = 18.18 ml / min
- ❖ titrated solution [I₂] = 0.1 mol / l
- ❖ titrant solution [Na₂S₂O₃] = 0.2 mol / l
- ❖ catalyst mass = 300 mg
- ❖ Reaction temperature: 430°C

3. Results and discussion

3.1. Characterization results

The differential thermal and gravimetric analysis (ATD-ATG) of the various supports is an important preliminary study which allows the choice of the activation temperature of the supports. The decomposition of boehmite is done in two stages: A first mass loss of around 25%, accompanied by an endothermic peak with a maximum around 75° C. This stage is attributed to the vaporization of the physisorbed water on the surface of the support. The mass loss profile is in agreement with the endothermic events of the ATD. Second loss in the range of 200 to 450°C is due to loss of water and transformation into boehmite, ie conversion of boehmite to transition alumina γ. The thermal decomposition of the titanium xerogel shows the existence of an endothermic peak until 150°C, which corresponds to a loss of 15% due to the elimination of physisorbed water and alcohol trapped in xerogel pores and dehydroxylation of Ti-OH. The second loss of mass at 375°C corresponds to the passage of the titanium oxide from the amorphous state to the crystallized anatase phase.

The curve of the thermal analysis of SiO_2 shows a loss of mass of the order of 8% up to 100°C which corresponds to the removal of water weakly adsorbed and / or trapped in the pores of the xerogel and to the loss of ethanol from silica condensation and polycondensation reactions, a small loss around 230°C is attributed to the loss of surface hydroxyls and / or the loss of traces of organic compounds chemically bound to the area. ATG shows a continuous loss up to 950°C , which can be attributed to the progress of the condensation reaction and the removal of surface silanol groups to give SiO_2 . the structural study of the supports (SiO_2 , TiO_2 and Al_2O_3) calcined at 400°C by X-ray diffraction, will make it possible to identify the nature of the phases formed after calcination at 400°C , the identification of the present phases is done by comparison of the diffractograms with the ICDD base (international center for diffraction data) version of 2010 integrated into the operating software High score. Figure 5 shows the X- Ray diffratograms of supports. The diffractograms of the different supports are represented in Figure 5, as expected; this analysis shows the formation of the metal oxides. Phase $\gamma\text{-Al}_2\text{O}_3$ PDF files (ICDD 00-051-0769), which crystallizes in a cubic face-centered structure. The anatase TiO_2 phase, PDF files (ICDD 00-001-0562), which crystallizes in a quadratic (tetragonal) structure. The SiO_2 diffractogram presents a part of the silica is crystallized in a tetragonal structure, PDF files (00-39-1425), with the presence of a broad peak for low values in 2θ . The X-ray diffractograms of the vanadium catalysts in Figure 6 put the existence of the V_2O_5 phase on the supports $\gamma\text{-Al}_2\text{O}_3$, TiO_2 and SiO_2 . Vanadium pentoxide crystallizes in an orthorhombic structure [11]; moreover, the observed phases are ($\gamma\text{-Al}_2\text{O}_3$, anatase of TiO_2 and quartz of SiO_2)

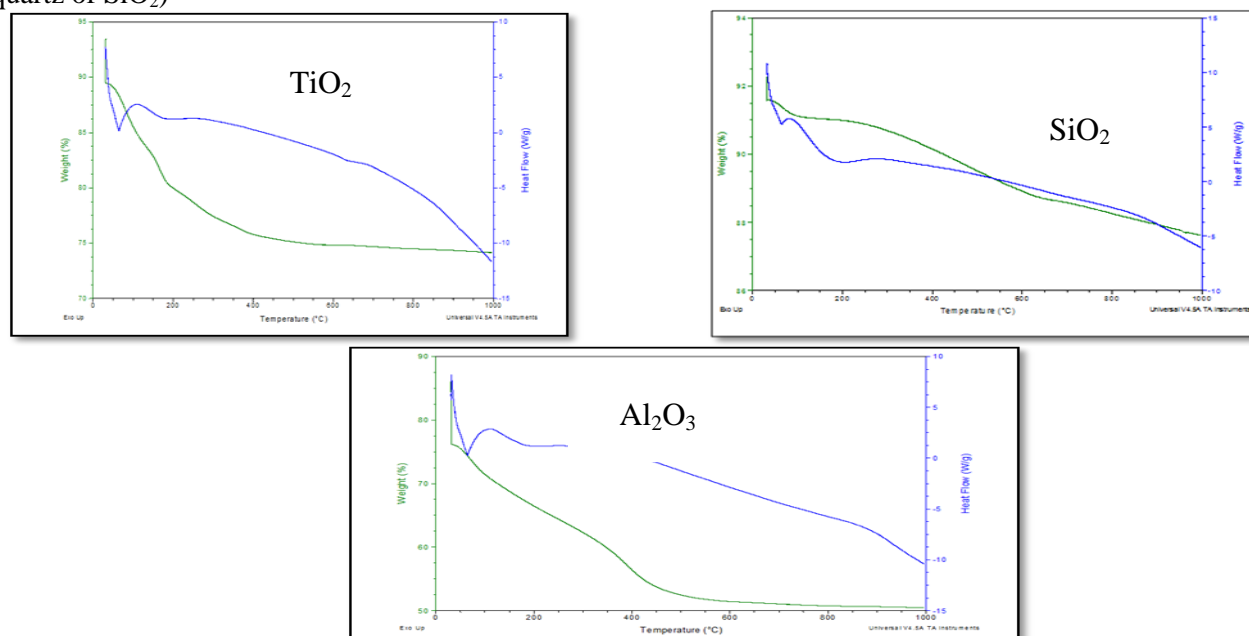


Figure 4: TDA / TGA analysis of various supports.

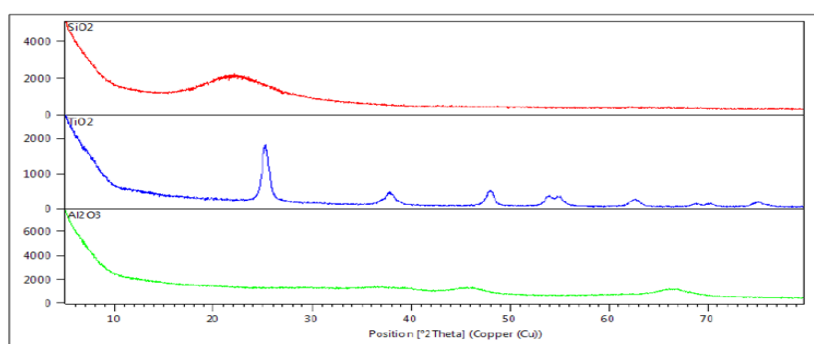


Figure 5: X-ray diffraction pattern of supports.

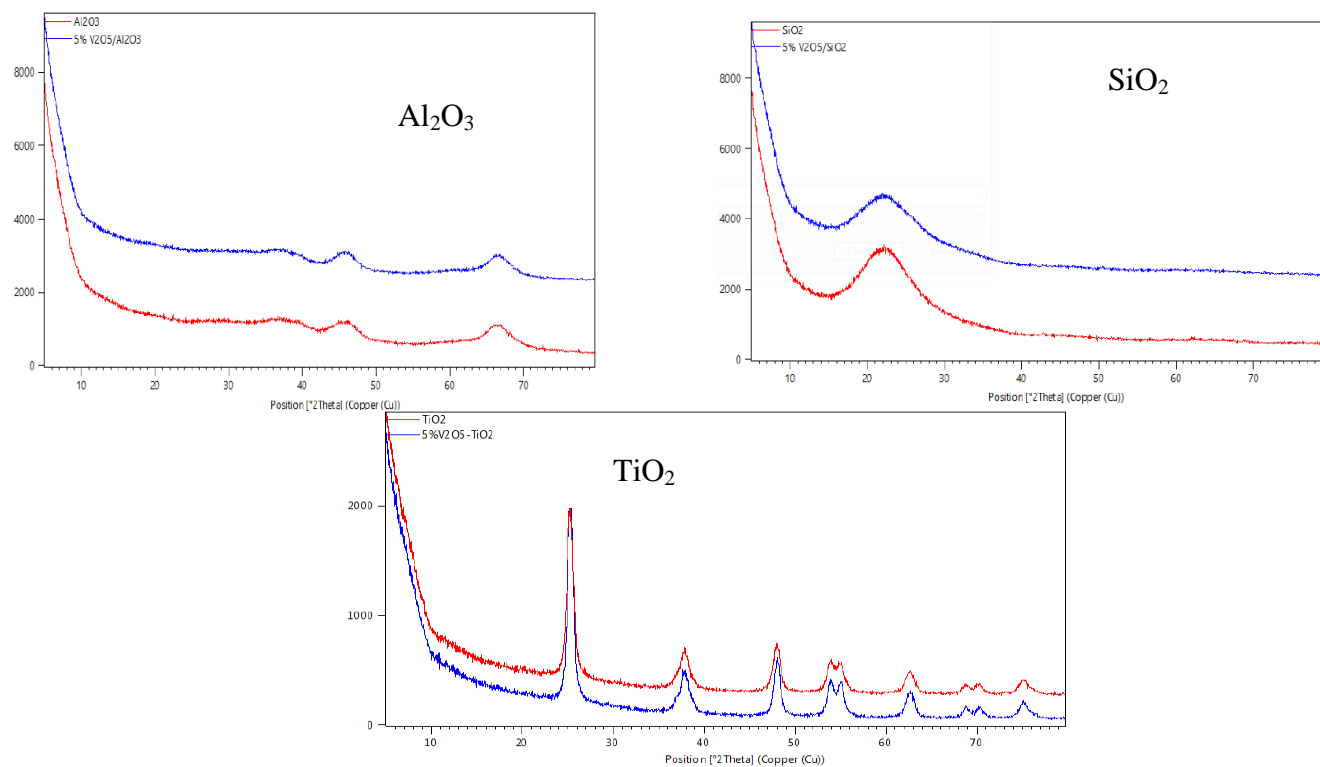


Figure 6 : Diffractograms of catalysts based on V_2O_5 .

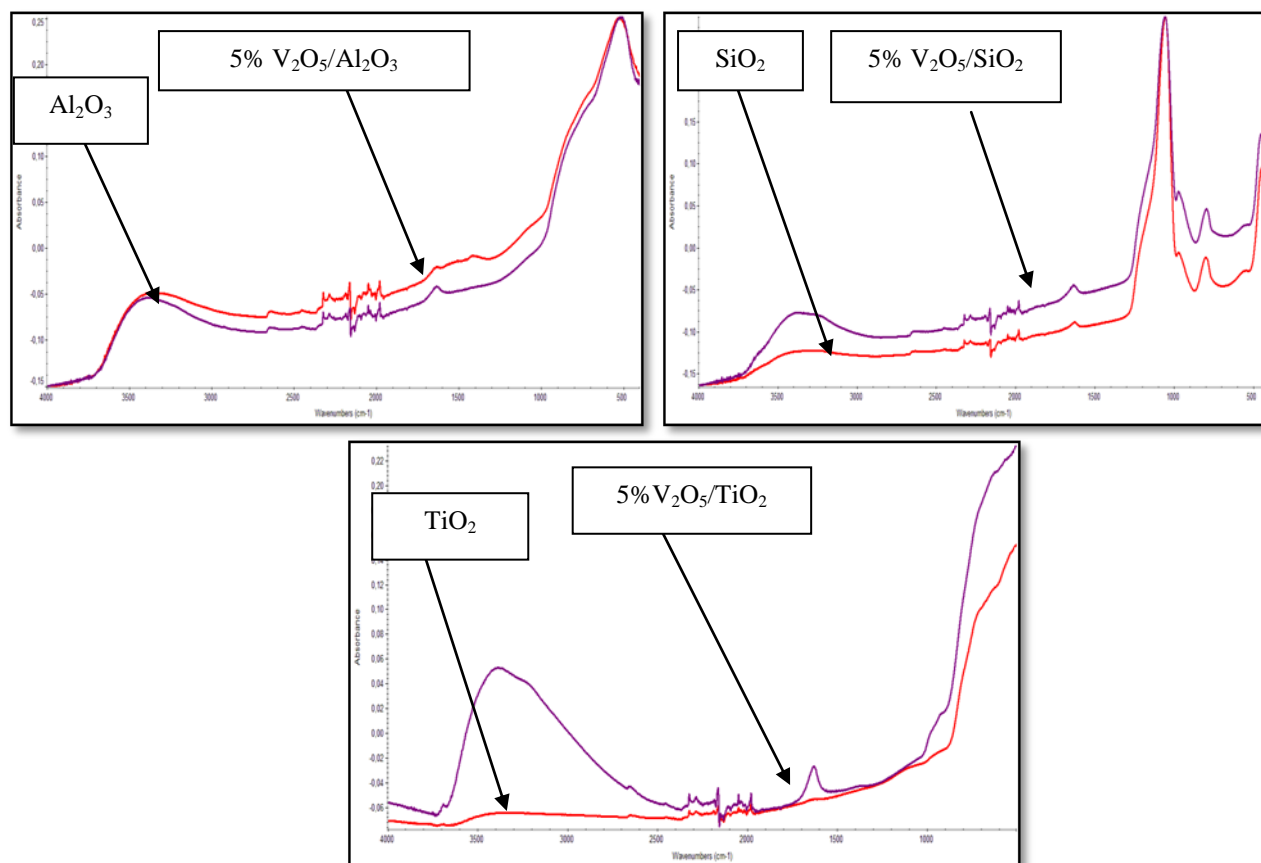


Figure 7: FT-IR spectrum of various samples.

The spectrum of the IR of the titanium oxide represented in Figure 7, it shows the presence of a broad band located at 3300 cm^{-1} attributed to the hydroxyl group [12], a very fine band located at 1623 cm^{-1} characteristic of the physisorbed water, and a wide band between 900 cm^{-1} and 400 cm^{-1} characterized by TiO_2 [13]. The addition of the vanadium quantity shows the appearance of a band towards the low numbers of waves located at 988 cm^{-1} which attributed to the vibration $\nu(\text{V}=\text{O})$. The IR spectrum of Al_2O_3 shows the presence of a broad band in the region of 3000 to 3400 cm^{-1} attributed to the surface hydroxyl groups. The absorption bands between 900 cm^{-1} and 1000 cm^{-1} correspond to a V-O shoulder. In the case of $\text{V}_2\text{O}_5\text{-Al}_2\text{O}_3$, we observe absorption at 550 cm^{-1} characteristic of the V-O-V band in the polyvanadate. For $\text{V}_2\text{O}_5\text{-SiO}_2$, an absorption band around 3000 cm^{-1} is observed corresponding to the vibration of the Si-OH isolated silanol groups [14-16]. The band at 1600 cm^{-1} is due to the torsional vibration of the water molecules [17]. At 1100 cm^{-1} , this band corresponds to the asymmetric elongation vibration of the Si-O-Si band [18-19, 17, 20]. The 947 cm^{-1} band is attributed to the asymmetric elongation vibration of the Si-O-V band [18, 19, 17, 21]. The band observed at 793 cm^{-1} corresponds to the symmetrical elongation vibration of the Si-O-Si band [18, 15, 19, 17, 16, 21]. The microscopy images of the supports are presented in Figure 8. On the right of each image are the EDX values which represent the chemical composition of the surface examined.

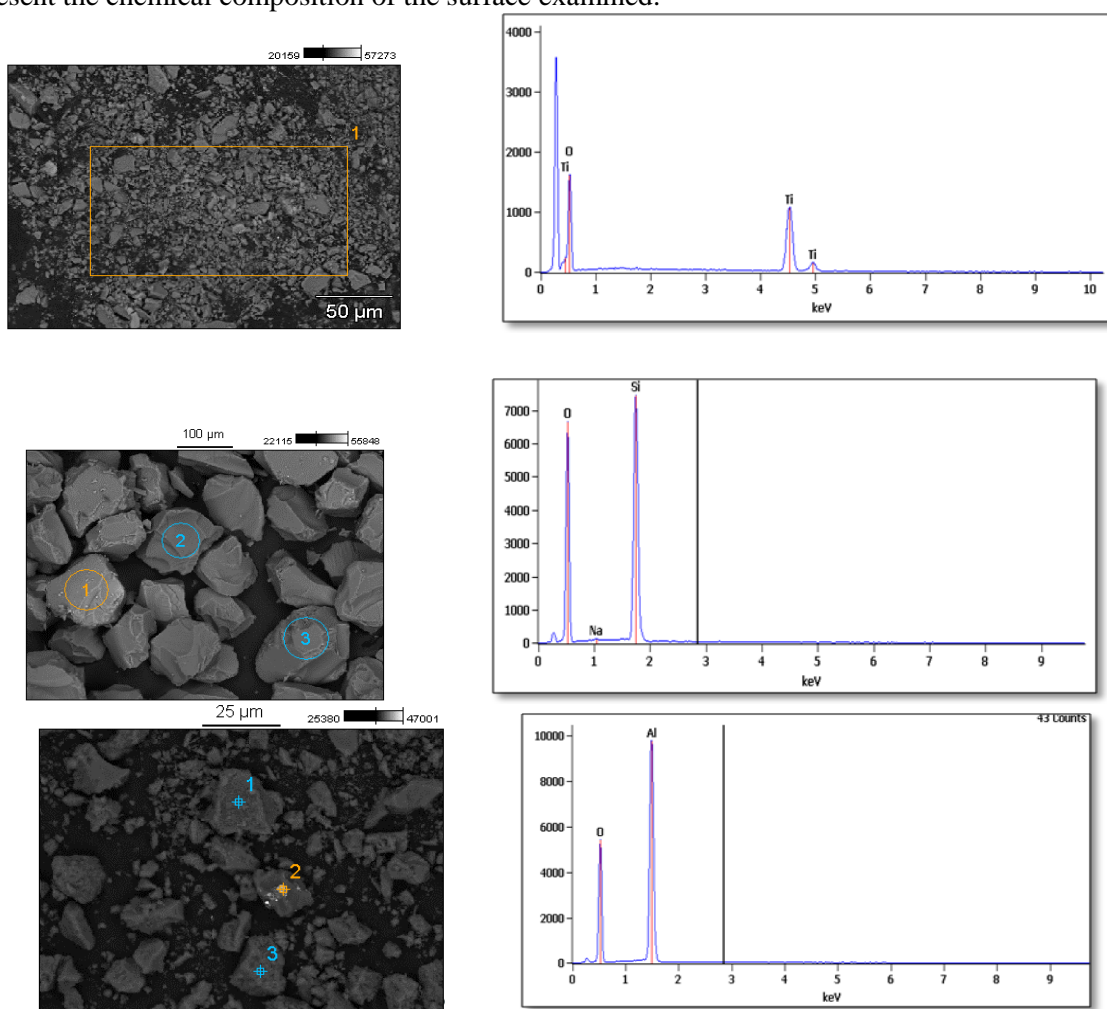


Figure 8: SEM / EDX image for supports.

The support for $\gamma\text{-Al}_2\text{O}_3$ it is clearly highlighted the presence of small particle sizes compared to silica which has a homogeneous surface of large particle sizes centered in $100\text{ }\mu\text{m}$. Similarly for TiO_2 the particles are very well crystallized. It is also noted that the particles of the TiO_2 supports have a good morphology and are in spherical form.

The SEM image of 5% V_2O_5 / TiO_2 oxide shows the existence of well-crystallized particles coexisting with very small grains. The values measured by EDX for vanadium in the oxides studied are very close to those predicted theoretically, which indicates good homogeneity of the materials. The 5% mixed oxide V_2O_5/SiO_2 is in the form of well crystallized faceted grains with a size of approximately 2 μm . They coexist with other larger grains. On the other hand, the SEM image for the 5% oxide V_2O_5/Al_2O_3 shows the existence of an agglomeration of small heaps of grain has been noticed. The values measured by EDX for vanadium in the various solids studied are shown in Table 2. The values are very close to those predicted theoretically with 5% in Vanadium. Analysis by EDX shows vanadium content varies between 4 and 5. Knowing the real vanadium content for these samples, the difference between the two values is explained by the fact that EDX is a surface analysis, very localized, which would give non-representative results if the sample is not very homogeneous.

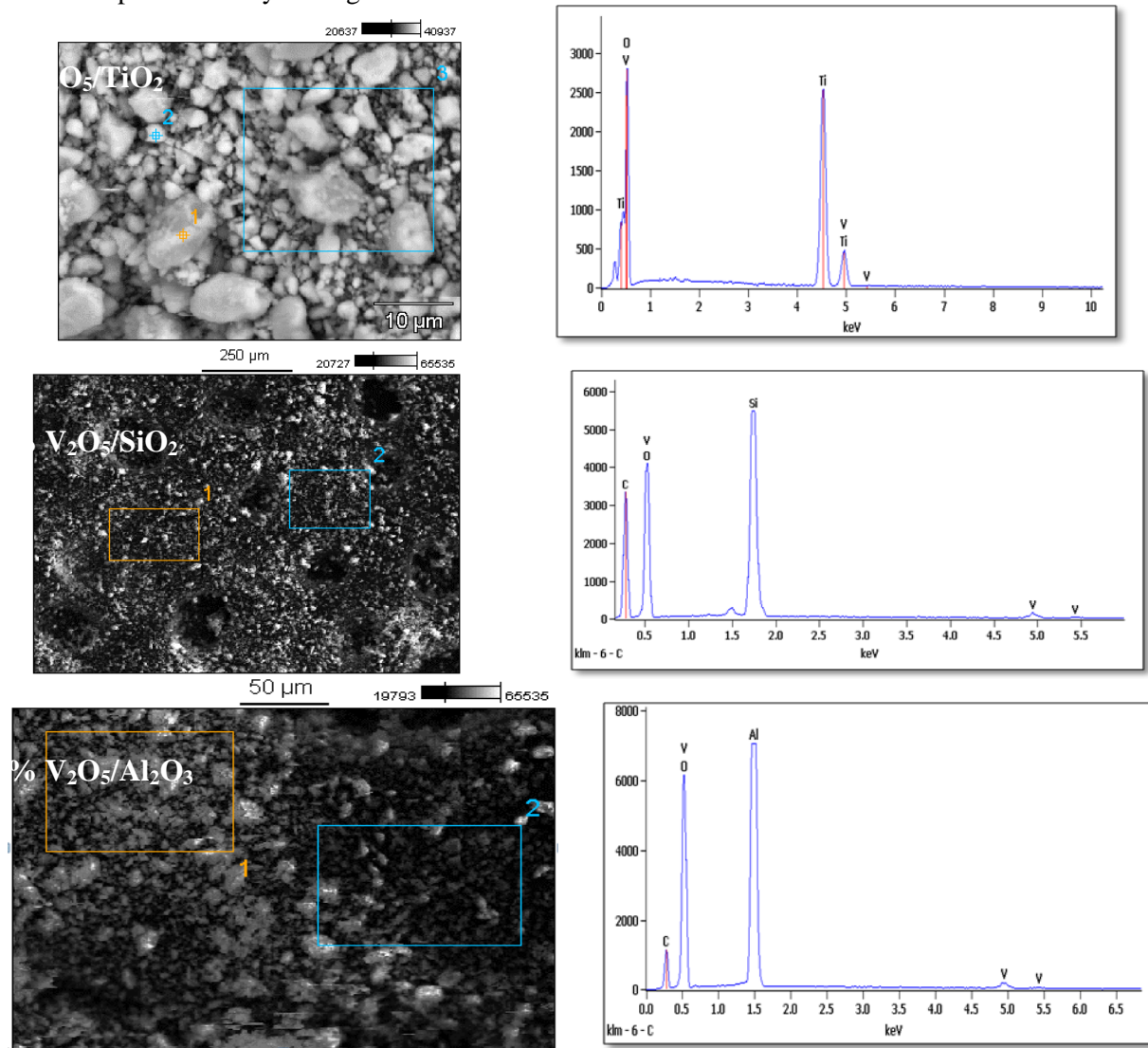


Figure 9: SEM / EDX image for oxides 5% V_2O_5/MO_2 .

Table 2: The values measured by EDX for vanadium.

solids	The values measured by EDX
5% V_2O_5/Al_2O_3	5.08%
5% V_2O_5 / TiO_2	5.01%
5% V_2O_5/SiO_2	4.05

3.2. Sorption isotherms

The N₂ adsorption and desorption isotherms of the 5 % V₂O₅-SiO₂, Al₂O₃ and TiO₂ samples calcined at 400°C as well as the BJH ((Barrett, Joyner and Halenda) distribution of the pore sizes are shown in table 3. According to the IUPAC classification [22], the 5% V₂O₅-SiO₂ curve is a type IV isotherm with a mesoporous structure with H₂ type hysteresis and has a surface area of 390.10 m² g⁻¹.

Table 3: Specific surfaces, porous volumes, and pore diameters of different materials.

Materials	BET surface m ² /g-1	Porous volume cm ³ /g-1	Pore diameter BJH (nm)
5% V ₂ O ₅ /SiO ₂	390.10	0.63	6.23
5% V ₂ O ₅ /TiO ₂	86.95	0.25	10.63
5% V ₂ O ₅ /Al ₂ O ₃	348.40	0.41	4.14

About the 5% V₂O₅-Al₂O₃ and 5 % V₂O₅-TiO₂ materials, the curves show type IV isotherms associated with an H₂ type hysteresis loop that is often obtained with rigid stacks of spherical particles of uniform or associated size to a capillary condensation in the mesoporous structure. The specific surfaces obtained for the two materials 5 % V₂O₅-Al₂O₃ and 5 % V₂O₅-TiO₂ are respectively 348, 40 and 86, 95 m² g⁻¹.

3.3. Decomposition of isopropanol

The results of the catalytic activity obtained after the oxidation of the oxides at different reaction temperatures are reported in Figure 10.

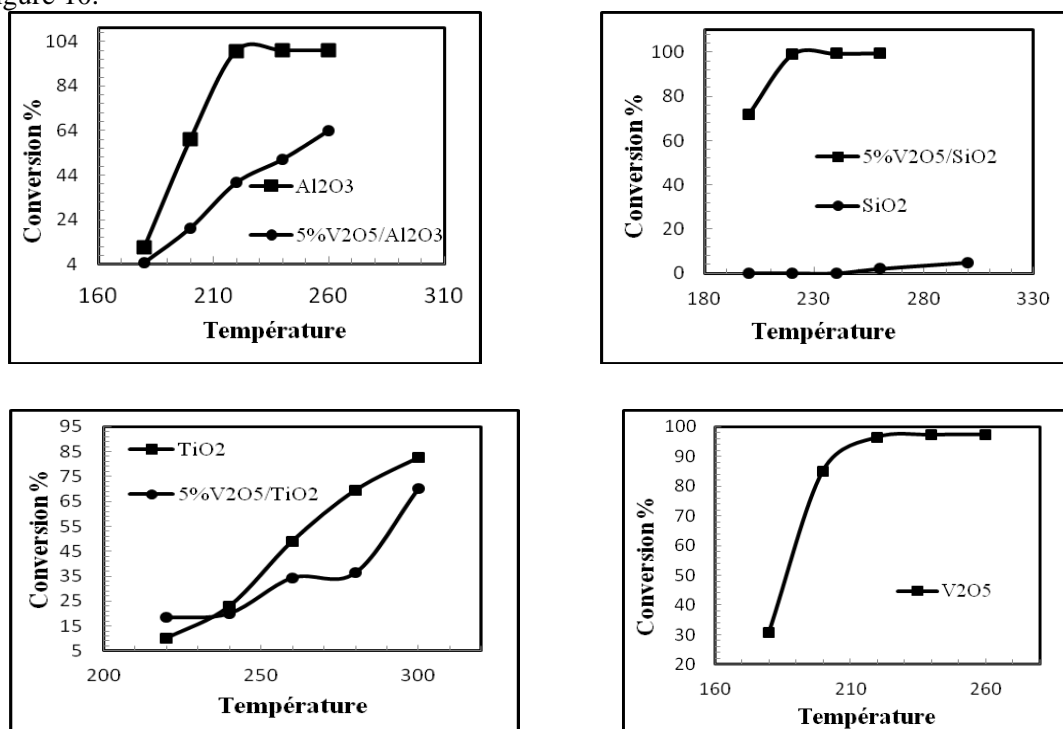


Figure 10: Isopropanol conversion curves of different oxides.

- ❖ the oxides are active in the decomposition reaction of isopropanol and the catalytic activity varies on all the oxides to reach maximum values on TiO_2 and Al_2O_3 .
- ❖ the increase in the temperature of the reaction results in an increase in the conversion of isopropanol to reach at 300°C maximum activity on all oxides.
- ❖ Raising the reaction temperature rather favors the dehydration of isopropanol by giving propene which increases regularly as a function of temperature to reach about 75.93% for TiO_2 , 100% for Al_2O_3 moreover, SiO_2 does not exceed 5% at 300°C .
- ❖ The formation of vanadium species on the surface of the oxides is accompanied by an augmentation of the acidic sites for SiO_2 and Al_2O_3 . During the addition, the vanadia species titrate the surface hydroxyls and encrete in the carrier oxide by mounting the $\text{V}^\pm \text{O}^\pm$ support bonds [23].
- ❖ Vanadium oxide (V_2O_5) contains Lewis and Brønsted acid sites. It should be noted that the formation of vanadium species on the surface of the oxides is accompanied by the reduction of the acid sites of Lewis and an augmentation of the Brønsted sites, moreover, the Brønsted sites can be present as a bridge of the V-OH sites support.
- ❖ The decomposition of isopropanol to propene and / or acetone is a widely used characterization test for the demonstration of the acid-base properties of catalysts. The results of the literature indicate that the dehydrogenation of alcohol to acetone is able to reveal the basic character of the catalysts. However, this last point remains controversial because the formation of acetone can also involve a mechanism of oxydo-reduction and this, particularly at low temperature. At high reaction temperature, only basicity is involved in the production of acetone [8].

The results of the catalytic oxidation of SO_2 on the various synthesized oxides represented in Figure 11, show that silica has a high oxidation percentage of 21% compared to the other supports (TiO_2 and Al_2O_3). Its results can be explained by the effect of sulfation. Dunn et al [24] have shown that SiO_2 does not contain basic hydroxyl functionalities and therefore does not form surface sulfate layers in the presence of SO_2 .

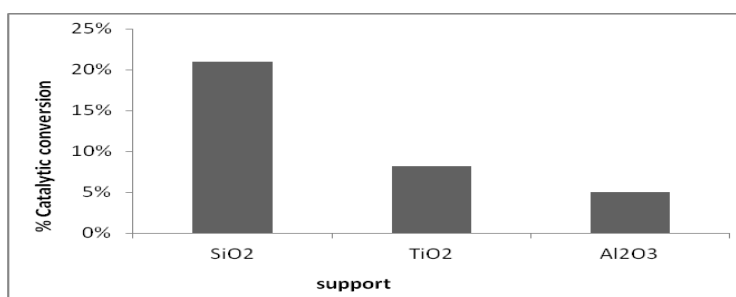


Figure 11: Catalytic oxidation of SO_2 en SO_3 by different support.

After adding vanadium (Figure 12), we notice a decrease in SO_2 conversion for SiO_2 , in addition the conversion by TiO_2 , Al_2O_3 is increased.

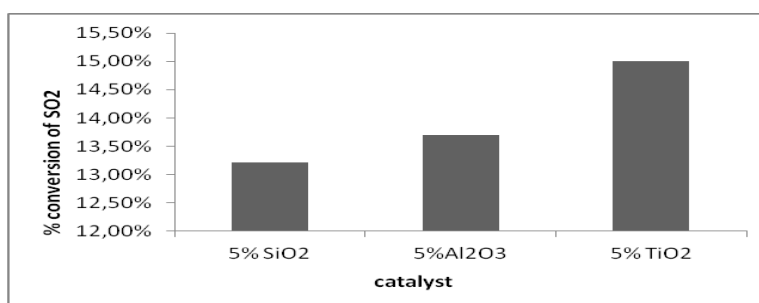


Figure 12: Catalytic oxidation of SO_2 en SO_3 by different oxides.

- ❖ This study shows that the 5% V_2O_5 / TiO_2 catalyst has a high SO_2 conversion rate relative to the silica-based catalyst and alumina; this can be explained by the reduction of the acid sites after adding 5% vanadium (see isopropanol decomposition results).
- ❖ The activity of these catalysts indicating in agreement with previous work that the more the electro negativity of the oxide cation is low, the more the $V\pm O\pm M$ carrier is basic and the higher the activity is to the adsorption and oxidation of the molecule of SO_2 [24].
- ❖ The results of the catalytic oxidation show that the bridging $V\pm O\pm Ti$ bond is more basic (because Ti has a low electronegativity of 1.54) than $V\pm O\pm Al$ and $V\pm O\pm Si$, therefore vanadium supported on TiO_2 has been found to be an active and selective catalyst for the oxidation of the SO_2 molecule.
- ❖ According to the results of the BET we note that the catalyst characterized by low specific surface and pore volume has a significant catalytic activity.

4. Conclusion

In this work, several catalysts of 5% vanadium complexes with three metal oxides (Si, Al and Ti) were prepared by inorganic precursors via the sol-gel process. The effectiveness of these catalysts and their acid-base properties have been previously tested for the conversion of isopropanol and iodometric dosage. The prepared catalysts are tested for the conversion of SO_2 to SO_3 . For the characterization of the catalysts, we used the following techniques: X-ray diffraction which reveals that the V_2O_5 species is predominant in all the samples, its results are in agreement with the ATD / ATG analyzes which show that calcination at $400^\circ C$ supports leads to the formation of the target oxide. The conversion of SO_2 on vanadium catalysts depends on the electronegativity, the reactivity to oxidation of sulfur dioxide is apparently linked to the $V \pm O \pm M$ bond, the study of electronegativity shows that the higher electronegativity of the support cation gives less basic oxygen ($V \pm O \pm M$). The study of the acid-base properties by decomposition of isopropanol show that the bridging bond $V\pm O\pm Ti$ is more basic than $V\pm O\pm Al$ and $V\pm O\pm Si$, this is very interesting to emphasize because it could explain the efficiency of the catalyst 5% V_2O_5 / TiO_2 for the oxidation of SO_2 .

Acknowledgements

The authors gratefully acknowledge the financial and technical support from R&D department of OCP group.

References:

- [1] J.R. Anderson, M. Boudart, Catalysis, Science and Technology, Volume 8, Springer-Verlag, Berlin, Heidelberg (1987).
- [2] W.G. Davenport, M. J. King, SO_2 oxidation catalyst and catalyst beds, second ed., Sulfuric acid manufacture, New York, 2006.
- [3] H.F. Rase, Handbook of commercial catalyst, Heterogeneous catalyst, New York, 2000.
- [4] J. Regalbuto, Catalyst preparation, second ed., Taylor & Francis Group, New York, 2007
- [5] S. El-Korso, I. Rekkab, A. Bedrane S, Pirault-Roy L, C. Kappenstein, Bull. Mater. SC., 35 (2012) 1187-1194
- [6] S.M. Siahpoosh, E. Salahi, F. A. Hessari, I. Mobasherpour, Bull. Société Royale des Sciences de Liège, 85 (2016) 812-934.
- [7] M. Cherfini. Master, USTHB, Alger, (2011)
- [8] A. Saadi, K.Bachari, D. Halliche, C. Rabia, SC Fondamentales Eng. Nature et Technologie, 9 (2013) 02-08.
- [9] G.A. Parks, Chem. Rev., 65 (1965) 177.
- [10] D. Haffad, A. Chambellan, J.C. Lavalle, J. Mol. Catal. A., 168 (2001) 153.

- [11] R. Enjalbert, J. Galy, Acta cryst., C42 (1986) 1469-1472.
- [12] A. Danion, Thèse, Ecole Centrale de Lyon, France (2004).
- [13] H. Reguig, Chap III. Thèse, Université de Tlemcen, Algérie (2013).
- [14] A. Comite, A. Sorrentino, G. Capannelli, M. Di Serio, R. Tesser, E. Santacesaria, J. Mol. Catal. A: Chem., 198 (2003) 1-2.
- [15] V. Iannazzo, G. Neri, S. Galvagno, M. Di Serio, R. Tesser, E. Santacesaria, Appl Catal A-Gen., 246 (2003) 49-68.
- [16] V. Pârvulescu, C. Anastasescu, Su B. L., J. Mol. Catal. A: Chem., 198 (2003) 1-2.
- [17] F. Adam, T-S. Chew, J. Andas, Chin. J. Catal., 33 (2012) 518-522.
- [18] E. F. Aboelfetoh, R. Pietschnig, Catal. Lett. 127 (2008) 1-2.
- [19] D. Habel, J.B. Stelzer, E. Feike, C. Schroder, A. Hosch, C. Hess, A. Knop-Gericke, Caro J, Schubert H, J. Eur. Ceram Soc., 26 (2006) 3287-3294.
- [20] A. Oufakir, L. Khouchaf, M. Elaatmani, A. Zegzouti, G. Louarn, A. Ben Fraj, J. Non-Crys. Sol., 149 (2006) 45-46.
- [21] R. Neumann, M. Levin-Elad, Appl. Catal. A: Gen., 122 (1995) 85-97.
- [22] S. J. Gregg, K. S. W. Sing, Adsorption, Surface Area and Porosity, second ed., London, 1982
- [23] J. Dunn, P. Koppula, H. Stenger, I. Wachs, Applied catalysis B: Environmental, 19 (1998)103-117.
- [24] J. P. Dunn, G. Harvey, Jr. Stenger, I. E. Wachs, Catalysis today, 51 (1999)301-318.