

RESEARCH ARTICLE

ENHANCEMENT OF THE GASES YIELD DISTRIBUTION USING MODIFIED ZEOLITE ON THERMO-CRACKING POLYETHYLENE WASTE

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ABSTRACT

Today, the world is suffering from serious problems like, climate change, green gases, and increasing temperature degrees on earth which is strongly connected with the plastic waste problem. In that work, we reached out to fabricate heterogeneous catalyst (mainly green materials synthesis) composed of a bunch of ceramic composites (vanadium oxide, and Sliver NPS) assembled on a thin layer of zeolite. Various characterization had been carried out on fabricated composite like surface morphology TEM, XRD, and UV to evaluate prepared catalyst. Then novel composite catalyst has been applied it be applied to the degradation process of High-density polyethylene (HDPE) throughout the Gasification process in the fixed bed reactor. In order to apply to the catalyst, it has to build an optimization gasification system (Temperature, heating rate, reaction time, and catalyst loading ratio). Regarding results of final products (gas yield ratio, and solid char), the best-optimized parameters with highly efficient catalytic are used thermo cracking of PEHD is % 0.2 wt at temperature 650 °C for 1 hour. We observed Composite has a great effect on gases yields products, and solid waste char. For instance, in the existence of composite catalyst, the gases ratio methane, and Hydrogen is more than in absence of a catalyst. Another characterization had been performed on composites and final products such as SEM, GC, and EDX.

KEYWORDS

Zeolite, Sliver Nanoparticles, Vanadium oxides, Gasification, PE Waste

1. INTRODUCTION

Although the world seeks to more clean and renewable energy in most modern applications, we still essential need fossil fuels, due to it is still the basic backbone for most industries. Thus it should try to reduce the negative impacts resulting from using fossil fuels such as (reducing green gases, plastic waste problems, and halogenated organic materials). To convert HDPE, LDPE to fuel and beneficial products, we need to apply thermo cracking process, which means high applied temperature to break down long polymeric chains to liquid fuel or gases. So, the pyrolysis and gasification processes are the best way for energy recovery gasification is not more different from pyrolysis, except, in pyrolysis, we only replace atmospheric oxygen with nitrogen (Yao et al., 2017). Gasification is the oxidizing of plastic compounds at a certain temperature. Gasification is the thermal oxidizing conversion of carbonaceous compounds to gaseous hydrocarbons in the presence of air at temperatures of 900°C–1100°C. The process uses plastic waste asphaltic sludge to high dry solids. The advantage of gasification is that it can produce sufficient gases to power steam in both the thermal dryer, as well bi-products of gasifier process is an inert residue suitable for landfill, and it does not negatively affect on water underground and soil. The gasification process for petrochemicals materials is mainly based on their catalyst activity, and reaction

mechanism methods, for example, methanol synthesis and Fischer-Tropsch synthesis (Bertau et al., 2014; Maitlis and de Klerk, 2013). Hundreds of organic products that result from indirect gasification are composed entirely of carbon, hydrogen, and oxygen, and a rare amount of nitrogen and sulfur (De Klerk, 2007). To get rich hydrocarbon compounds using gasification, it should take into consideration some factors like reaction temperature, the catalyst used (cost, thermal, and physical stability during the process, active surface area, and eco-environmental, and reaction time (De Klerk, 2008).

Zeolites are widely used in many petrochemicals industrial catalytic processes due to possessing unique characteristics like shape selectivity surface adsorption with active sites furthermore, it is green materials, easily recyclable, and non-toxic, and too cheap comparing other catalysts.

To identify the negative effect of combination V_2O_5 and between interaction, and influencing the stability of FCC catalysts, numerous researchers and mining engineers works on combination between the interaction between V_2O_5 and zeolite Y (FCC catalyst) in various petrochemicals process but on the other side thought that vanadic acid could be formed during the process, which is similar to phosphorous acid reaction, to promote the hydrolysis of OH group, then easily destroy zeolite structure (Jones, 1991; Wormsbecher et al., 1986). Later, Pine et al.

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and Xu et al. proposed that co-existed sodium ions and cationic ions could be the main reason for the destruction of zeolite in high temperatures (Pine, 1990; Xu et al., 2002).

Various catalysts have been applied in pyrolysis and gasification for polymeric materials and plastic waste in order to improve the product selectivity and enrich gases yields like high gas products and syngas yields. With regard to recent literature, several nanomaterials were applied and got high stability and activity such, as transition metals modified clay, zeolite modified, ceramic matrix (Saad et al., 2017; Sun et al., 2012). Meantime, many attempts have been pinpointed on the expansion of rare-earth metals, and transition metals like iron, Nickel, magnesium vanadium oxide as passivating agents (Jeon et al., 2006). However, it usually fails to passivate vanadium under the circumstance of regeneration. Recently, that metals compounds have been applied in many FCC catalysts as passivating agents (Wallenstein et al., 2015; Akah, 2017). Konta et al. also checked up silver vanadium oxides solution at alkaline medium p^H between 7 and 14 and the temperature around 273 to 298 K, addition to applied on various oxides such as $R-AgVO_3$, $\hat{a}-AgVO_3$, $Ag_4V_2O_7$, and Ag_3VO_4 which were synthesized from alkaline solutions of $AgNO_3$ and either NH_4VO_3 or Na_3VO_4 . According to the previous studies, the existence of oxygen as a carrier for the gasification process, it greatly promotes the efficiency and reduces the tar and waxes products (Konta et al., 2003; Albrecht et al., 2007; Rapagna et al., 2000). On the other hand, Zhifeng Hu et al., mentioned the effect of oxygen on reaction mechanism during the process will give rich syngas yields (Hu et al., 2012; Hu et al., 2019). They notify that yields of H_2 and CO were directly increased with the addition of an oxygen carrier.

The first hydrocracking process evolved over 8 decades ago. It was based on acid-modified clays Centi, G. &, Perathoner, S. (2008) but zeolites and aluminosilicates were announced later. Clays are still used in some cases such as in treating some heavy fractions. Clays with different acidities can be acquired by thermal treatment before preparing the catalyst. The temperature of the thermal treatment of clay determines the type and concentration of the hydroxyl groups (Herrero et al., (1990) and this thereby determines its acidity. Montmorillonites or acid-modified montmorillonites have been used for numerous reactions. The occurrence of diffusion limitation can be used to the benefit of the catalytic process, for example, to enhance the selectivity of the reaction. This is illustrated in the toluene disproportionation and xylene isomerization reaction over ZSM-5, where the diffusion of the desired product p-xylene is much faster; that is, the diffusional time constant is much lower than that of the unwanted products o-xylene and m-xylene.

In order to improve the catalytic performance has been demonstrated for mordenite, zeolite Y, [10] ZSM-5, and zeolite beta (Swabb and Gates, 1972; Verboekend and Perez-Ramirez, 2011). The beneficial effect of the use of small zeolite crystals on the overall reaction rate is twofold. First, smaller crystals have shorter intracrystalline diffusion path lengths, hence the reaction products are released more rapidly. Accordingly, fewer secondary reactions like coke formation and cracking are observed. Second, more micropore entrances are present per weight amount of zeolite. This induces higher accessibility of the zeolite crystals and therefore may result in a net increase in the overall activity. It was claimed that alkaline-treated mordenite displayed preserved crystallinity and a significantly increased benzene adsorption capacity. Moreover, catalytic evaluation in gas-oil hydrocracking revealed a 3 times higher conversion for an alkaline-treated Pd/mordenite than for the untreated zeolite (Liang et al., 2021; Kostyniuk et al., 2021). Already then, Young speculated that the improved performance of the modified material could be due to better access to the micropores. Utilizing organ-modified clay received much attention since clay layers create a tortuous path against the permeant, yielding better barrier properties, especially for gases (Abdelrahman et al., 2021).

2. EXPERIMENTAL

2.1 Material

All chemicals were purchased from Sigma Aldrich, Egypt, products (vanadium oxide (V_2O_5 (99.9 % Purity), zeolite ($Na_{12}(AlO_2)_{12}(SiO_2)_{12} \times 27H_2O$) was and sliver Nanopowder High-density polyethylene (HDPE B1054) was purchased from, SABIC, Egypt.

2.2 Instrumentation

UV-vis absorption measurement was investigated using Model: Perkin Elmer, Lambda 750 spectrophotometer in the range of 150–1000 nm, double beam spectrometer permit transmittance, Transmission electron microscope (TEM) imaging analysis of the samples was conducted using a Zeiss Evo 18 instrument. crystallinity analysis was also investigated using Bruker, D8 Advance X-ray diffraction (XRD), operated a copper (Cu)

source TDG measurement for PEHD was used Analyzer (Q500), design sample masses between 0–200 mg.

The gasification system ware built up using a fixed bed reactor (SS 315, 0.97 mm ID). The height of the reactor is 34 cm. which is heated using an electric furnace. Two valves (inlet, and outlet) as a wall as a union connection to the reactor. Pressure gauge to count pressure during the experiment PEHD plastic sample and other additives placed inside bottom section of the reactor. electrical furnace ($65 \times 8 \times 25 \text{ cm}^3$), operated by thermocouple the released gases yield gases collected using quartz tuber, then gases have been characterizing using GC/MS Model: Agilent Technologies, 7890A, located in the environmental department in Beni-suef university, Egypt addition to char (black carbon) are collected and weight and be ready to analysis throughout Energy Dispersive X-Ray Analysis (EDX).

2.3 Catalyst Preparation

Zeolite sample was immersed in an alkaline solution at 65°C for 30 minutes using Na OH (0.6 mol/L) alkaline solution based on previous information related to the desilication procedure (Verboekend et al., 2011; Hagiwara et al., 2003; Possato et al., 2013). To prepare suspended solution V_2O_5 /Zeolite, emerging 0.25 g of zeolite inside 20 ml of polar solution 1:1 (water: Ethanol), leave it till dried centrifuge and filtrated, then. dissolve 0.5 g of V_2O_5 in 20 ml distilled water, add modified zeolite in solution, ultrasonic for 5 hrs. 60°C .

2.4 Preparation of (Ag_3VO_4) Compound and Its Composite

In order to Synthesis of a solution of Ag_3VO_4 , add 0.5 g of Ag_2O to a solution containing 0.055 g (of V_2O_5 , then add 0.2522 g of HF (aq) in a heat-backfilled with 40 mL of deionized H_2O . Up to seven pouches of varied then put inside the autoclave to perform reactions by using one pressure vessel. Adjustable autoclave at temperature 150°C for 24 h, then the cooling rate of $6^\circ \text{C}/\text{h}$. With the opening, the pouch and vacuum-filtered will get an Ag_3VO_4 (Albrecht, et al.2007). Eventually, to get catalyst composite, Blind 0.5 g of vanadium zeolite with 0.5 of Ag_3VO_4 , incinerated for 2 hours at 700°C , cooling overnight to be ready to applicable.

3. RESULTS AND DISCUSSION

3.1 Surface Morphology

3.1.1 SEM characterization

Figure (1) manifests the morphology structure of the zeolite and zeolite /vanadium samples. there are elite differences was appeared on the zeolite surface due to some depletion aggerated of vanadium oxides on the zeolite surface. it can describe as truncated-side cubic crystals on across section zeolite around $0.5\text{--}2 \mu\text{m}$. This detecting is confirmed interaction forces between zeolite anion exchange and nano vanadium structure, addition arranged as the random molecule is wrapped up inside the pore channels of zeolite.

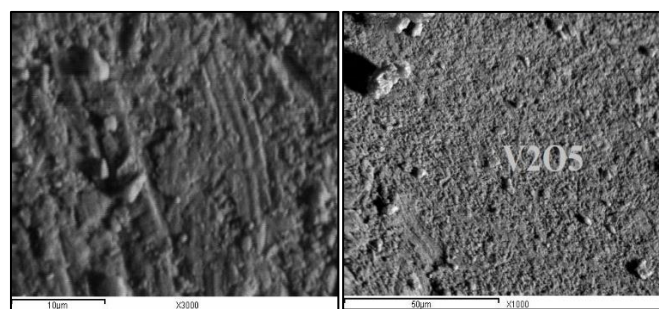


Figure 1: SEM images zeolite & Assembled V_2O_5 on surface zeolite

3.1.2 TEM characterization

TEM micrograph of zeolite / V_2O_5 is depicted in Figure 4. It can be noticed that the zeolite sample has a uniform distributed and the bigger particle size is around 110–220 nm. also, V_2O_5 is random distribution in a different area on zeolite surface, it could be V_2O_5 filled our voids and gaps (inter-inter space) zeolite. With regard to TEM Fig. (2), we observed the Ag atoms are deposited on the zeolite layers and occupy the interlayer space between zeolite molecules due to the smallest size around 5 to 15 nm and its crystalline structure of silver nanoparticles. In other meaning, there is a diversion from a quantum bloc to a metallic particle bonding with the continuous growth and fluctuation of the nanoparticles on the surface of the zeolite structure. although the appearance of various Ag- nanoparticles

and spread on the whole zeolite surface but there is coalescence, and depletion in different parts of zeolite, it leads to a decrease in the activity of active sites between them.

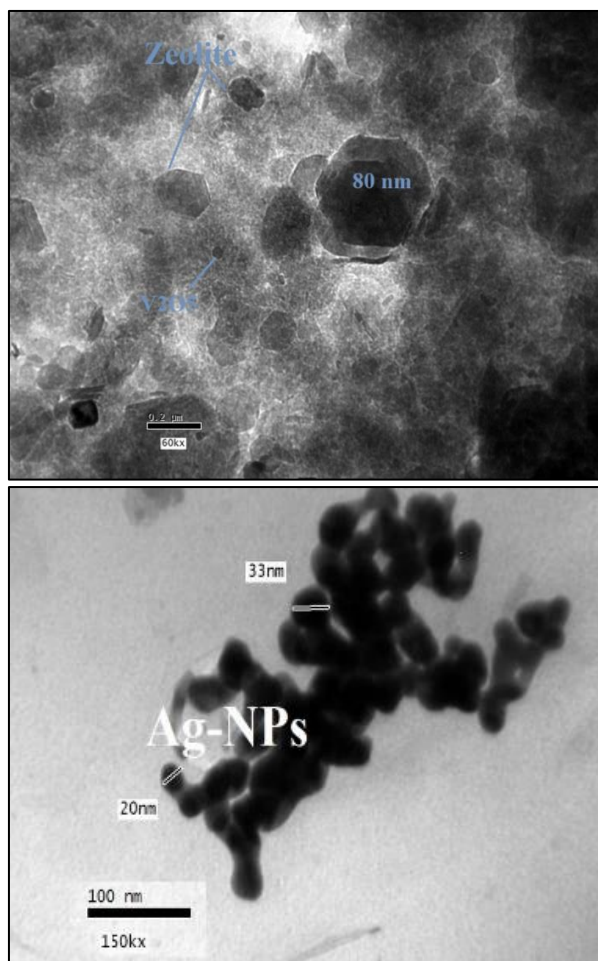


Figure 2: TEM images V_2O_5 / zeolite compound, & Ag-NPs

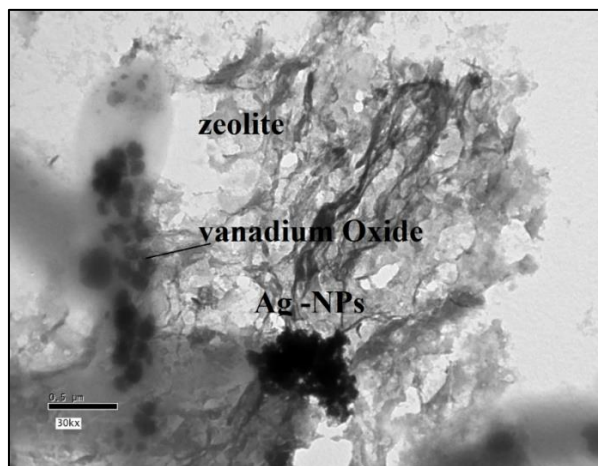


Figure 3: Representative TEM V_2O_5 / Zeolite /Ag Composite

The TEM image in figure (3) is illustrated the capacity and uniform spread of Vandome oxide, and graphene nanoparticles spread on zeolite surface solution V_2O_5 has unique morphology dissociation on clay surface our explanation, it could be cations exchange clay cations, and Vandome Metals or return back the electronic configuration of iron: $[Ar] 3d^6 4s^2$ (ferromagnetism), it is loss e- to be half field d-orbital outer shell with forming chelating complexes with anion (silicate, and aluminate) of zeolite structure. as well the Nano size structure of Vandome around 15 nm and its crystallographic shape, which is also facilities to make chelating complexes with other compounds. in case graphene assembled on clay. Which has seen in figure (3) various zeolite layers flocculated has appeared on the spread area on the clay surface. Graphene is the main reason for aggregation and depletion of a thin layer of zeolite based on Vander Waals interaction forces between molecules.

3.1.3 XRD characterization

3.1.3.1 XRD zeolite

With regard fig (4), The XRD patterns of zeolite and its additives describe several sharp peaks at 2θ values of 7° , 10.2° , 12.6° , 16.4° , 22.6° , 24° , 26.6° , 27.8° , 31° , 31.6° , 31.7° , 32.7° , 33.4° , and 34.5° is agree with previous literature,³⁷ which was indexed to the (200), (220), (222), (420), (440), (600), (622), (640), (642), (694), (600), (841), (842) and (662) casting back the cubic crystalline structure. as far. there is no big change zeolite / V_2O_5 samples. which it shows the same pattern, with specific peaks related to vanadium oxides, our explanation, it could back vanadium oxides nanoparticles fill out voids interlayer space, which lead to resulting in the decrease of crystallinity.

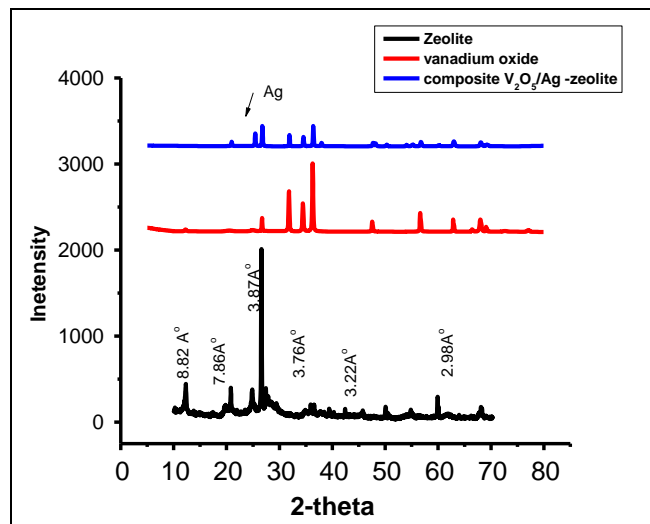


Figure 4: XRD zeolite, vanadium oxide, and composite

The above XRD spectra display that composite of papered catalyst that is composed of a different anionic species moreover minerals, such as; sodium, silicate, aluminate, and quartz. This mineral has an octahedral crystal structure made of crystallized silica (silicon dioxide, SiO_2), throughout figure (4), we observed several sharp peaks are impurities identical to quartz and silicate. There are some diffraction peaks that appear at (001), (110), (210) plane at 2θ 82, 35, and 66. The X-ray diffraction analysis of vanadium oxides powder (Figure 4) manifests different peaks has been investigated at 2θ ($^\circ$) = 18.7, 32.1, 34.5, 36.2, 44.2, 55.5, 56.0, 62.6, and 74.6 are allocated to (V_2O_5).

3.1.3.2 Polyethylene high density (PEHD) thermo-gravimetric characterization

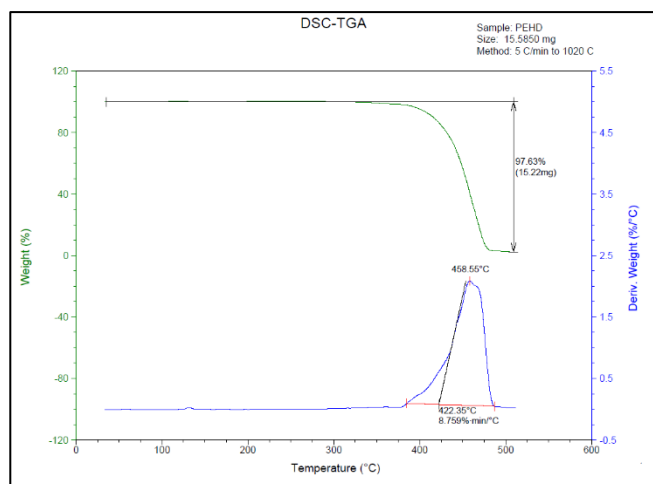


Figure 5: Show DSC -TGA of HDPE

Curve PEHD showed in Figure 5 reveals a decline peak at $458^\circ C$ due to changing the solid phase to the liquid phase at glassy temperature. at a certain temperature the large polymeric materials of PEHD start to break down to saturated and unsaturated monomers, hundred of reaction mechanism occurs, leading to forming liquefied gases. The main reason for that measurement, we need to know which best temperature will be completely converted to gases without liquid or waxes. At $458^\circ C$ we

noticed, several unsaturated and long-chain hydrocarbon results, thus we applied gasification on PEHD at 600 °C to get rid of all waxes residual. Fig (5) points out the decomposition HDPE at a flow rate of 10 C/min. there are big changes in polyethylene mass fraction around 400 °C to 520 °C. As well as release bi-products (CO, CO₂, and H₂O) from the polymeric carbon chain. However, at a certain temperature of 422 °C the polymeric PEHD is lost 8.795 % min/c of its weight.

3.1.4 UV-vis absorption analysis

To evaluate and measure silver, and vanadium inside papered, we should utilize UV-vis spectra. Samples was performed around 200 to 1000 nm to figure 6 is pointed out, there are three different peaks silver nanoparticles solution, zeolite /vanadium oxide, and their composite silver nanoparticles appear strong peak at 270 nm, addition to another peak was appeared specified for vanadium oxide /zeolite compound, which is slightly shifted absorbance peak 297 nm, furthermore, appearing as weak peak to explain the spectrum shifted, it might be returned, oxidation of v^{+2} to v^{+3} , v^{+5} with zeolite structure (many anion exchanger (SiO₃, Al⁺³, Ca⁺², Na, and SiO₂). As far, we notice abroad peak as far specific for the colloidal solution, which contains all species, might due to creation of active sites between silver, and vanadium (metallic bond), addition assembled of silver, vanadium particles on the surface of the zeolite.

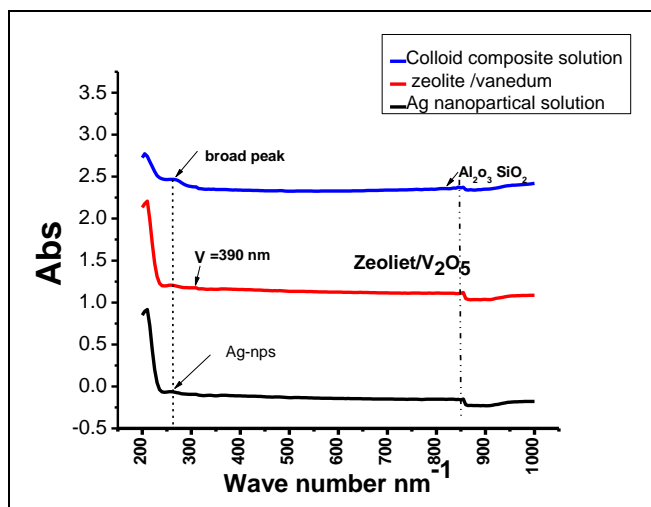


Figure 6: UV-Vis-NIR analysis silver NPs, zeolite /V2O5, and their composite in colloid solution

The UV-Vis diffuse reflectance characterization in the region (Fig. 6) confirm distinct outcome for the impregnated vanadium samples. From the previous information, the peak intensity is an indicator for the vanadium atoms spectra in this region which are located range 325–500 nm, as well as confirming the transfer of low energy electrons between O and V5+ v outer shell vanadium atoms in octahedral coordination (Gao and Wachs, 2000; Burcham et al., 2000). On the other hand, we noticed a little shift to peaks ranging 270–340 nm is concerning to coordination of the tetrahedral of vanadium. Two peaks are a good indicator for charge transfer resulting from oxidizer V²⁺ to V⁵⁺, and reduction of zeolite throughout anionic terminals and oxygen anions.

3.2 Studying the Optimized Parameters of the Degradation Process

Present, zeolite and its modified are mainly utilized in the cracking process of the petrochemical industry. It mostly used as an active adsorbent catalyst for many processes during the purification and decoloration of crude oil. that sorts of hetero- catalysts is working on cracking of heavy fractions, etherification, esterification, alkylation, dehydration, and hydration of hydrocarbon compounds (Yang et al., 2002).

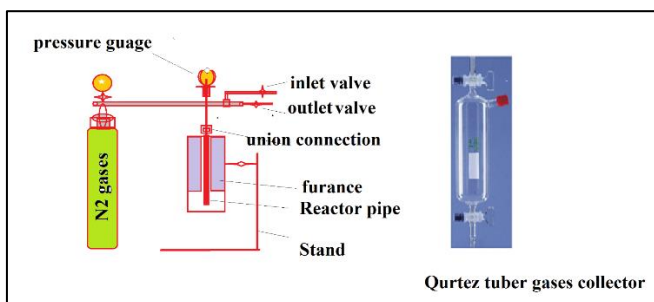


Figure 7: Gasification system

Figure (7) points out the gasification design used for thermos-catalytic degradation of a sample polyethylene high density, it should selective specific parameters to obtain high efficiency of gases and solid waste. There are various factors affecting reaction mechanisms such as temperature, the catalyst used, time of reaction, and pressure. We reported a gradual increase in pressure and temperature during one hour to be stable.

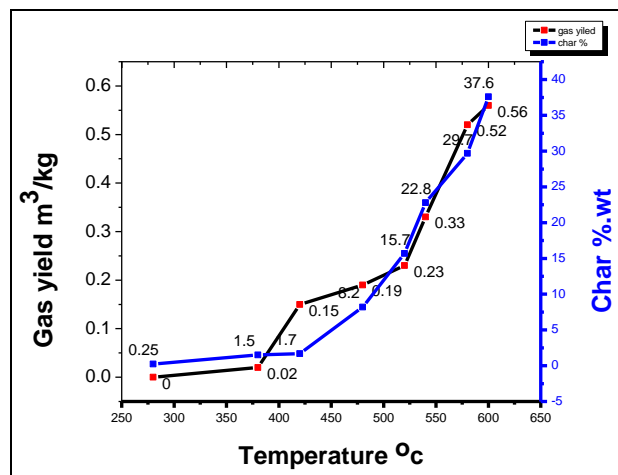


Figure 8: PEHD Gasification in presence Zeolite

Regard figure (8) illustrated the gasification of polyethylene high density using zeolite without modified. There are gradually increase both solid char, and gas yield with increasing temperature gas yield is increases 0.25 to 37.6 m³/kg addition to, char solid also increase to be maximum amount 0.56 at 650 °C. With the highest values of the resulting char solid, there is no good cracking conversion of plastic PE compared to modified zeolite composite at the same reaction conditions (temperature, reaction time).

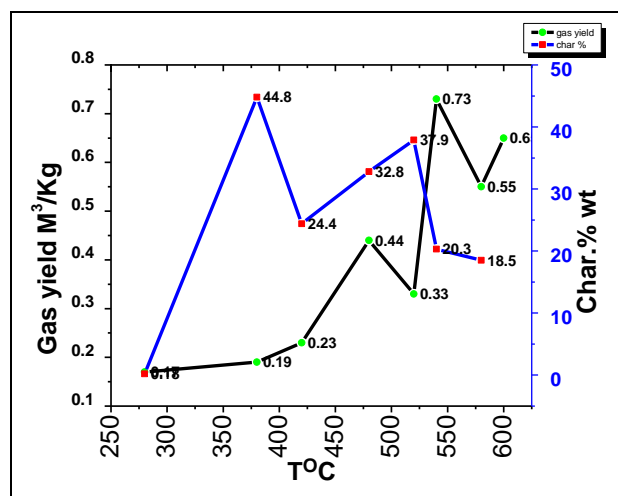


Figure 9: PEHD Gasification in presence Zeolite/V₂O₅/Ag

While using 0.2 g of prepared zeolite /V₂O₅/Ag composite on gasified PEHD sample, we noticed there are big changes in gas yield and char solid. Gas yield is gradually increased from 0.18 to 0.44 at 475 °C then dropped to 0.33 at 525 °C then to return back 0.73 high value of gas yield at 550 °C That is a good indicator for effective of modified zeolite composite on distribution on PEHD surface based on active sides of anionic exchange and electrochemical cell V³⁺Ag⁰ //V⁵⁺Ag (redox-oxidizing state). On the other hand, solid char is also gradually increased till reaching maximum amount 44.8% wt at 350 °C then steadily declined to 18.5 at 575°C. That is results are affirmed on the optimized temperature for gasification polyethylene high-density to gases at 550 °C (high gas yield, and lower solid char) as shown in figure (9)

3.2.1 Gases Yield distribution characterize

Hundreds of organic molecules resulting from the thermal degradation of polyethylene at certain conditions (heating rate, and reaction time) and process parameters (sample, catalyst loading ratio). Gas yield distribution for different cases is shown in fig (10). First, without applied zeolite, Nemours of unsaturated hydrocarbons like alkenes, alkynes, and heterocyclic compounds, addition to High ratio of solids char carbon (CO,

CO₂). But that saturation is comparatively different in case using nature zeolite, with the presence of oxide organic compound like (, benzoic acid, phenolic compounds) results of gasification and there are obviously increasing in gases yield than char carbon. In case modified catalyst (V₂O₅-Zeolite-Ag), there are high indications for both quality and quantity of gas yields as well as reducing of heterocyclic, and unsaturated compounds, and increase paraffinic compounds.

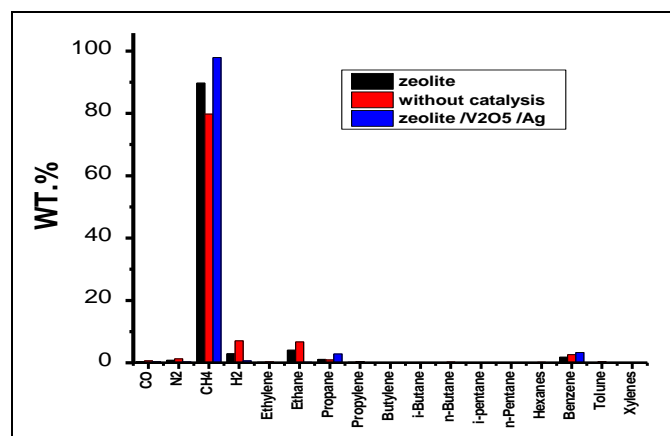


Figure 10: GC analysis for PEHD Gasification in presence Zeolite/V₂O₅/Ag

3.2.2 Solid char characterization

Carbon Char has many industrial applications as raw material or adsorbent materials, catalyst, and incineration. Thus, we reached to convert plastic waste (PE) to gases and solids char, without liquid and waxes at convenient temperature 550°C to 600°C. regarding the TEM image in fig (11), we noticed the brightness of metals in the char sample, which confirms the stability of the prepared catalyst during the gasification process as well as complete conversion for plastic PE.



Figure 11: TEM Gasified PEHD Char sample

3.2.2.1 EDX characterization

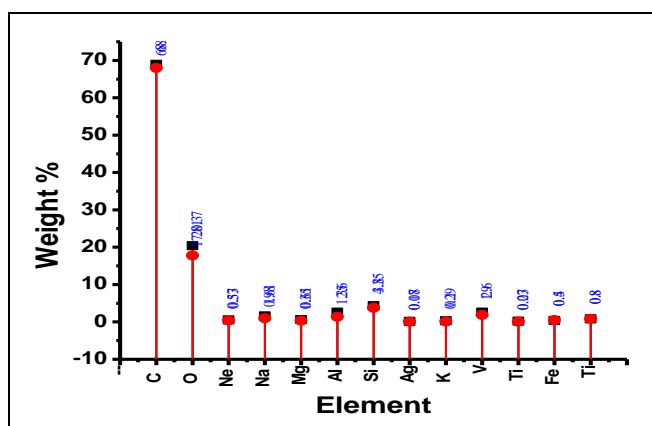


Figure 12: EDX Gasified PEHD Char sample

Furthermore, when applied EDEX on char sample, we found, the sample contains a strain of metals element which are the main content of our composite, like vanadium, Na, silicate, silver, and carbon. it is a good inductor to integrate element with char which enrich the quality of char as bi-product or raw material reused.

4. CONCLUSION

The aim of this study was to get active catalyst higher efficiency than nature zeolite, as well as enrich gas yield products, and quality of light hydrocarbon and paraffinic compounds. in that work, we reached to get hetro catalyst works on the degradation of polyethylene high-density to distribution gases without wax (erosion, pipes blocked) and liquid compounds event at 550 °C for 45 minutes. Furthermore, high conversion of plastic to lower amount of solids char (easily remove from the fixed reactor, and be applicable to another field) Catalyst is composed of vanadium oxide, Nanosilver, and zeolite substrate not only highly ratio of gases yields distribution, but also the quality of gas products like syngas, Hydrogen, and paraffinic compounds. The conjunction between metals alloy (vanadium, and silver) on zeolite anion exchange cross-section is the main reason for reducing active energy, to complete conversion for PE at 550°C. The deposition, and assembly of vanadium oxides and silver on zeolites layer sheets enhance the activity of zeolite catalyst regard to previous results and measurements. That integration is also created several active sites on the zeolite surface, which lead to forming a chelating complex during transition phase temperature, then created several of saturated hydrocarbon and paraffinic light compounds.

REFERENCES

- Abdelrahman, A., Radwan, A.M., Zaki, A.H., Hamouda, A.S. 2021. Assembling a Bunch of Transition Metals Oxides on Sodium Montmorillonite Layer for Anionic Polymerization of Butyl Methyl Acrylate. *Journal of Nanostructures*, 11(1), pp. 1-12.
- Akah, A. 2017. Application of rare earths in fluid catalytic cracking: A review. *Journal of Rare Earths*, 35(10), pp. 941-956.
- Albrecht, T.A., Stern, C.L., Poeppelmeier, K.R. 2007. The Ag₂O–V₂O₅–HF (aq) System and Crystal Structure of α-Ag₃VO₄. *Inorganic chemistry*, 46(5), pp. 1704-1708.
- Bertau, M., Offermanns, H., Plass, L., Schmidt, F., Wernicke, H.J. eds. 2014. Methanol: the basic chemical and energy feedstock of the future, pp. 677. Heidelberg: Springer.
- Burcham, L.J., Deo, G., Gao, X., Wachs, I.E., 2000. In situ IR, Raman, and UV-Vis DRS spectroscopy of supported vanadium oxide catalysts during methanol oxidation. *Topics in Catalysis*, 11(1-4), pp. 85-100.
- De Klerk, A. 2007. Environmentally friendly refining: Fischer–Tropsch versus crude oil. *Green Chemistry*, 9(6), pp. 560-565.
- de Klerk, A. 2008. Fischer–Tropsch refining: technology selection to match molecules. *Green Chemistry*, 10(12), pp. 1249-1279.
- Gao, X., Wachs, I.E., 2000. Investigation of surface structures of supported vanadium oxide catalysts by UV- vis- NIR diffuse reflectance spectroscopy. *The Journal of Physical Chemistry B*, 104(6), pp. 1261-1268.
- Hagiwara, K., Ebihara, T., Urasato, N., Ozawa, S., Nakata, S., 2003. Effect of vanadium on USY zeolite destruction in the presence of sodium ions and steam—studies by solid-state NMR. *Applied Catalysis A: General*, 249(2), pp. 213-228.
- Hu, Z., Jiang, E., Ma, X. 2019. The effect of oxygen carrier content and temperature on chemical looping gasification of microalgae for syngas production. *Journal of the Energy Institute*, 92(3), pp. 474-487.
- Hu, Z., Ma, X., Chen, C. 2012. A study on experimental characteristic of microwave-assisted pyrolysis of microalgae. *Bioresource technology*, 107, pp. 487-493.
- Jeon, H.J., Park, S.K. and Woo, S.I. 2006. Evaluation of vanadium traps occluded in resid fluidized catalytic cracking (RFCC) catalyst for high gasoline yield. *Applied Catalysis A: General*, 306, pp. 1-7.
- Jones, R.L. 1991. Oxide acid-base reactions relating to the inhibition of vanadium attack on REY zeolite catalysts. *Journal of Catalysis*, 129(1), pp. 269-274.

- Konta, R., Kato, H., Kobayashi, H., Kudo, A. 2003. Photophysical properties and photocatalytic activities under visible light irradiation of silver vanadates. *Physical Chemistry Chemical Physics*, 5(14), pp. 3061-3065.
- Kostyniuk, A., Bajec, D., Likožar, B. 2021. Catalytic hydrogenation, hydrocracking and isomerization reactions of biomass tar model compound mixture over Ni-modified zeolite catalysts in packed bed reactor. *Renewable Energy*, 167, pp. 409-424.
- Liang, J., Shan, G., Sun, Y. 2021. Catalytic fast pyrolysis of lignocellulosic biomass: Critical role of zeolite catalysts. *Renewable and Sustainable Energy Reviews*, 139, pp. 110707.
- Maitlis, P.M., de Klerk, A. eds. 2013. *Greener Fischer-Tropsch Processes: For Fuels and Feedstocks*. John Wiley & Sons.
- Pine, L.A. 1990. Vanadium-catalyzed destruction of USY zeolites. *Journal of Catalysis*, 125(2), pp. 514-524.
- Possato, L.G., Diniz, R.N., Garetto, T., Pulcinelli, S.H., Santilli, C.V., Martins, L. 2013. A comparative study of glycerol dehydration catalyzed by micro/mesoporous MFI zeolites. *Journal of catalysis*, 300, pp. 102-112.
- Rapagnà, S., Jand, N., Kiennemann, A., Foscolo, P.U. 2000. Steam-gasification of biomass in a fluidised-bed of olivine particles. *Biomass and bioenergy*, 19(3), pp. 187-197.
- Saad, J.M., Williams, P.T. 2017. Pyrolysis-catalytic dry (CO₂) reforming of waste plastics for syngas production: Influence of process parameters. *Fuel*, 193, pp. 7-14.
- Sun, Z., Luo, S., Qi, P., Fan, L.S. 2012. Ionic diffusion through Calcite (CaCO₃) layer during the reaction of CaO and CO₂. *Chemical Engineering Science*, 81, pp. 164-168.
- Swabb, E.A., Gates, B.C. 1972. Diffusion, reaction, and fouling in H-mordenite crystallites. The catalytic dehydration of methanol. *Industrial & Engineering Chemistry Fundamentals*, 11(4), pp. 540-545.
- Verboekend, D., Mitchell, S., Milina, M., Groen, J.C., Pérez-Ramírez, J., 2011. Full compositional flexibility in the preparation of mesoporous MFI zeolites by desilication. *The Journal of Physical Chemistry C*, 115(29), pp. 14193-14203.
- Verboekend, D., Pérez-Ramírez, J. 2011. Design of hierarchical zeolite catalysts by desilication. *Catalysis Science & Technology*, 1(6), pp. 879-890.
- Wallenstein, D., Schäfer, K., Harding, R.H., 2015. Impact of rare earth concentration and matrix modification in FCC catalysts on their catalytic performance in a wide array of operational parameters. *Applied Catalysis A: General*, 502, pp. 27-41.
- Wormsbecher, R.F., Peters, A.W., Maselli, J.M., 1986. Vanadium poisoning of cracking catalysts: mechanism of poisoning and design of vanadium tolerant catalyst system. *Journal of Catalysis*, 100(1), pp. 130-137.
- Xu, M., Liu, X., Madon, R.J. 2002. Pathways for Y zeolite destruction: The role of sodium and vanadium. *Journal of Catalysis*, 207(2), pp. 237-246.
- Yang, H., Wilson, M., Fairbridge, C., Ring, Z., Hill, J.M., 2002. Mild hydrocracking of synthetic crude gas oil over Pt supported on pillared and delaminated clays. *Energy & fuels*, 16(4), pp. 855-863.
- Yao, D., Wu, C., Yang, H., Zhang, Y., Nahil, M.A., Chen, Y., Williams, P.T., Chen, H. 2017. Co-production of hydrogen and carbon nanotubes from catalytic pyrolysis of waste plastics on Ni-Fe bimetallic catalyst. *Energy Conversion and Management*, 148, pp. 692-700.

