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Optimization of Microwave-Assisted ZSM-5 (10) Catalytic Cracking to Maximizing Conversion and Energy Efficiency

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ABSTRACT

The potential application of microwave technology and interaction with oil/catalysts for heavy naphtha cracking to light products (aromatics and olefines) was explored. The reactor is a QVF tube of 240 mm long and 12.7 mm inner diameter, with 80 mm effective zone and the upper and lower zones filled with inert ceramic particles. The process used heater for heating heavy naphtha and condenser for the gas products. The feed enters the reactor after heating and the reaction occur within the catalytic zone while the ceramic particles improve the distribution of the compounds of the feed and products. All the products condensed and analysed by gas chromatography. Microwave technique used in chemical reactions in order to save energy and increase the conversion with lower temperature due to hot spots created within the catalyst. ZSM-5 (10) catalysts cracking experiments performed with and without nitrogen injection. The nitrogen injection increased the conversion in all conditions. The experiments achieved with various microwave irradiation (750–1250) W, preheating temperatures (150–250 °C) and space velocities (2 and 6 l/hr). The best result of cracking reaction conversion is (77.56%) at microwave power of (1250 W), a flowrate of (2 l/hr) and preheating temperature (200 °C). The cracking is facilitated due to re-activation effect of nitrogen on acid sites of the catalyst. The time of experiment is 12 minutes. Almost the flowrate has negative effect on the conversion. Microwave power increase reaction rate and increased the reaction conversion compared with conventional techniques. This study covered the effect of microwave with catalyst on the residence time, energy saving and conversion at lower temperature.

Keywords: microwaves, catalytic cracking, heavy naphtha, cracking reactor, microwaves and heterogeneous catalysis.

INTRODUCTION

Naphtha is one of petroleum refineries products 15–30 W% of crude oil and its boiling point between (30–200 °C) (Hammadi and Shakir, 2020). It is a complicated mixture contains hydrocarbon molecules with 4–12 carbon atoms, including paraffins (P), iso-paraffins (I), olefins (O), naphthene (N), and aromatics (A) (PIONA) (Abdullah et al., 2024). Some substances consist of heteroatoms such as sulfur, nitrogen, and oxygen. Additionally, metals such as vanadium, nickel, and silicon may be present. (Rahimpour et al., 2013). The conversion of naphtha are directly influenced by its composition, which is depending on its origin and location, (Antos and Aitani, 2014). The origins of naphtha are defined by a significant composition of aromatics and olefins which are among the many properties associated with molecule structure and chemical properties that define the substance's origins. (Da Silva et al., 2015).

Essential fundamental raw materials in the petrochemical industry are aromatic compounds. In the aromatics industry, benzene, toluene, and xylene (BTX), are the most essential organic raw materials. (Dehertog and Fromen, 1999). Nonetheless, the growing inconsistency between the depletion of petroleum and the increasing demand for aromatics becomes increasingly apparent. In 2018, global consumption of energy increased by 2.9% which it is the largest increase since 2010 (Jiang et al., 2020).

The catalytic cracking of naphtha, which consists of n-alkanes with carbon chain lengths ranging from C4 to C12, takes place under conditions of high operational temperature (Mohammed et al., 2010). The process involves high reaction temperatures and significant steam quantities in the feed to enhance the yield of ethene and propene (Abd et al., 2024). The technique allows us to examine the impact of catalyst activity, as well as its progression over time. This also provides information on the possible reversible and irreversible deactivation of the catalyst (Corma et al., 2012).

Zeolite is a porous medium composed of crystalline aluminosilicates that has high surface area and ability to adsorb molecules (Majeed and Majeed, 2017). There are two types of zeolites (synthetic, natural). ZSM-5 is suitable catalyst for naphtha cracking (Ahmedzeki et al., 2016). It is a synthetic type of zeolite (García et al., 2016). The catalyst's particulate size, shape, and porosity have significant effects on the hydrodynamics and rate of the reaction (Theyab et al., 2022). Due to its distinctive structures, acidity, shape selectivity, and thermal and hydrothermal stability, ZSM-5 is regarded as an effective catalyst in cracking process. (Khoshbin and Karimzadeh, 2017). Because of these properties, ZSM-5 can be used as a catalyst in hydrocarbon cracking, and other processes. ZSM-5 is typically produced from hydrogels via hydrothermal synthesis (Rane et al., 2008).

The microwave power for direct heating of materials is rapidly becoming an essential resource for several industrial processes due to its effective energy transfer mechanisms (Mohammed and Mohammed, 2013). The efficiency and effective application of microwave in cracking of heavy naphtha is the main goal to specified the best conditions for optimum cracking process. The microwave power have previously been demonstrated in several applications such as drying operations, sintering of ceramic components, metal processing, and plasma creation (Corma et al., 2012).

The application of microwave power is preferred for naphtha cracking because it can be achieved at lower temperature, higher conversion and lower energy consumption and this is one of our conclusions in cracking by assistant of the microwaves. In addition, microwave-assisted reactions are typically quicker and yield superior results compared to traditional approaches. The demonstrated microwave increased yields of the targeted aromatic product, and decreased presence of environmentally hazardous chemicals (Abd and Al-yaqoobi, 2023). The hydrocarbon processing sector of the chemical industry continually works to enhance the efficiency of its processing procedures due to the significant amount of energy consumption involved (Mora et al., 2010). The study introduces the relationship between the microwave power, flowrate and preheating temperature. All previous studied have not improve the products by altering the above parameters within the mentioned ranges.

MATERIALS

Feedstock

The raw material for the cracking process is heavy naphtha which have initial and final boiling point of 80 °C to 185 °C. The naphtha is obtained from the atmospheric fractional distillation unit of the Al-Najaf refinery. The PONA analysis of heavy naphtha was done by Basra oil company as shown in Table 1.

ZSM-5 catalyst

Spherical ZSM-5 (10) catalysts were utilized with particles size range between (2–3) millimeters and ratio of silicon to aluminum is 10:1 mol. (Congyi City Meiqi Industry and Trade Co., China)

Nitrogen gas

The nitrogen gas used as a carrier with 30 cm^3/min for 15 min before starting of experiment and also used to reactivate the catalyst.

EXPERIMENTAL METHOD

The catalytic cracking unit

The heavy naphtha catalytic cracking system was designed as a continuous flow unit with a

Table 1. PONA analysis of heavy naphtha

Composition	Wt.%
n-Paraffin	31.026
i-Paraffin	33.258
Naphthene	10.003
Aromatic	18.938
Olefine	1.169
Undefined	5.606

packed bed reactor. The components of this unit consist of a feedstock drum, feed pump, electrical preheater, microwave oven, QVF tubular reactor, cooling and condensation system, separator, gas flow meter, one way valve, and electrical power cabinet, the schematic flow diagram is shown in Figure 1.

Reactor

The reactor is a QVF tube of 500 mm long and 12.7 mm inner diameter, with a 240 mm reactor length within the microwave effective zone. Three equal packing zones with a height of 80 mm represent all the reactor inside the microwave oven. The middle zone contains desired catalyst, while the top and bottom zones contain inert ceramic particles with an average diameter of 5 mm. This arrangement increases distribution and prevents channeling, as illustrated in Figure 2. The upper zone is connected to a cooling and condensation system.

The feed stock stored in feed tank and then pumped through the heating element to the reactor which fixed in the center of the microwave oven. The exits product from the reactor enters the condenser which condense some of the products and the others was thrown to the outside of the laboratory (atmosphere). The condensate product collected and then analyzed by gas chromatography.

Figure 2. The reactor's three equal packing zones

CHARACTERIZATION OF THE ZSM-5 CATALYSTS

Various chemical, physical, and microstructural characteristics were needed to evaluate the materials. X-ray fluorescence (XRF), Fourier transform infrared spectrometer (FTIR),

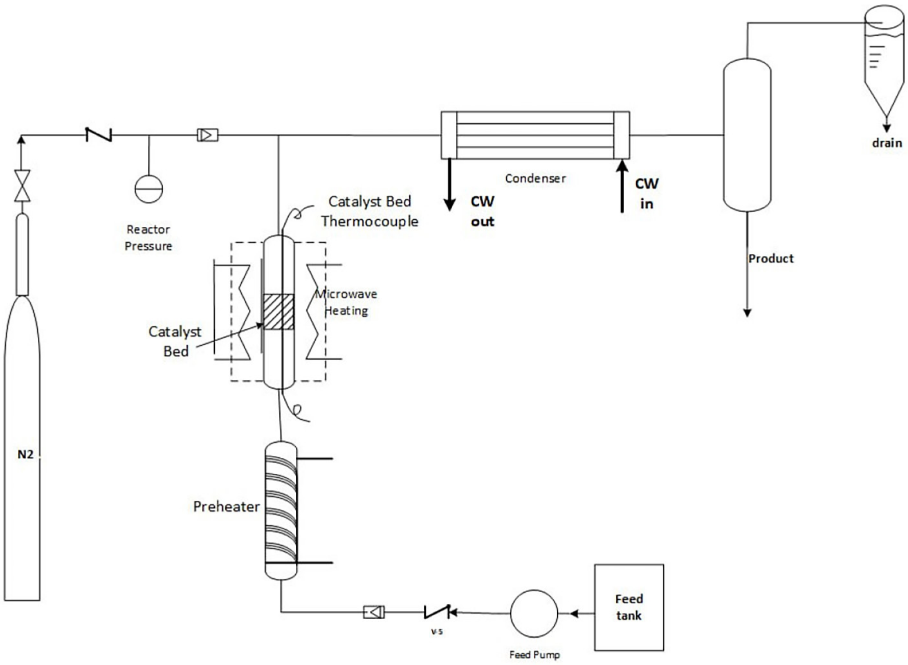

Figure 1. The catalytic cracking unit process flow diagram

Brunauer-Emmett-Teller (BET) specific surface area (SSA), Scanning electron microscopy (SEM), and X-ray diffraction (XRD) were utilized to evaluate the catalysts.

X-ray diffraction

The XRD patterns of ZSM-5 (10) is in full agreement with the corresponding values reported for zeolite (Sodium Aluminum Silicate) that has a chemical formula (Na_2 $Al_{1.9}$ $Si_{94.1}$ O_{192}) that matched (JCPDS, Card No. 00-048-0136) as shown in Figure 3. The zeolite (ZSM-5) samples have highly crystallinity.

Scanning electron microscopy

The different micrographs of SEM (10, 25, 50, and 200 kx magnification) show the details that are related to crystal forms, external surfaces, purity of the phases, and unknown species (if they are present; as illustrated below) as shown in Figure 4. There are two forms of crystals, one of them is in hexagonal shape and the other is

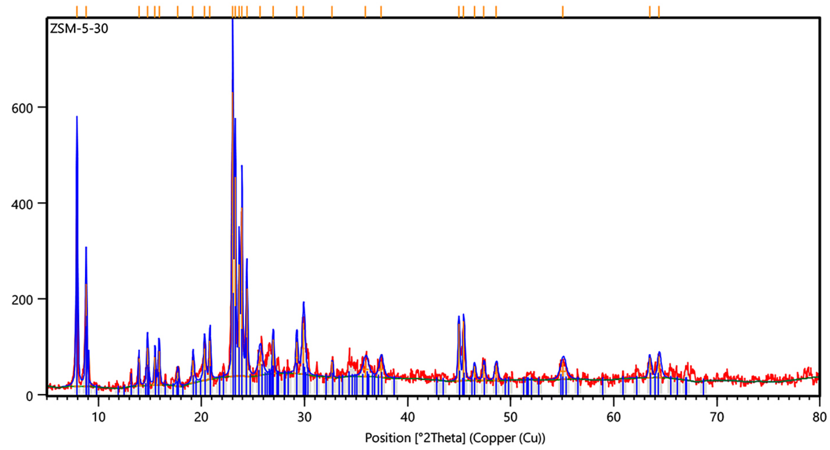

Figure 3. The XRD patterns of ZSM-5 (10) powders

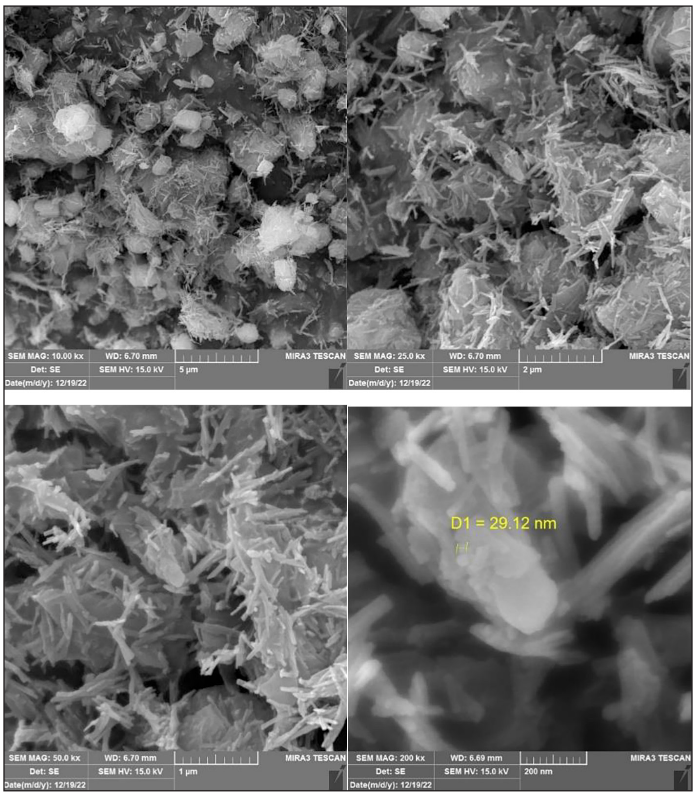

Figure 4. The micrographs of ZSM-5 (10)

rod-like shape with average diameter (29.12 nm). Moreover, crystal size distribution phenomena attributed to aggregation, twinning, and sometimes intergrowth. With lower magnification value, indication of single crystals was sensed.

Surface area and pore volume

The specific surface area and total pore volume of ZSM-5 (10) zeolite samples were measured by nitrogen physical adsorption using the Brunauer, Emmett and Teller method (BET). The highest SSA values caused by increasing the combined total pore volume gives higher cracking rate. Moreover, the zeolite ZSM-5 (10) samples show type IV isotherms with distinguishing hysteresis loops corresponding to mesoporous materials according to (IUPAC) classification of adsorption isotherms that shown in Figures 5 and 6. Table 2 give important features are the increase in adsorbed volume at higher p/p_0 as well as a hysteresis loop. A non-distinct increase of adsorbate volume in the low p/p_0 region in type IV isotherms indicates the absence of the micropores. The increase in adsorbed volume at higher p/p_0 in type IV isotherms is caused by capillary condensation below the expected condensation pressure of the adsorbate. Capillary condensation is a secondary process that requires the preformation of an adsorbed layer on the pore walls which formed by multilayer adsorption. Both processes generally occur simultaneously in range of 0.3–1 p/p_0.

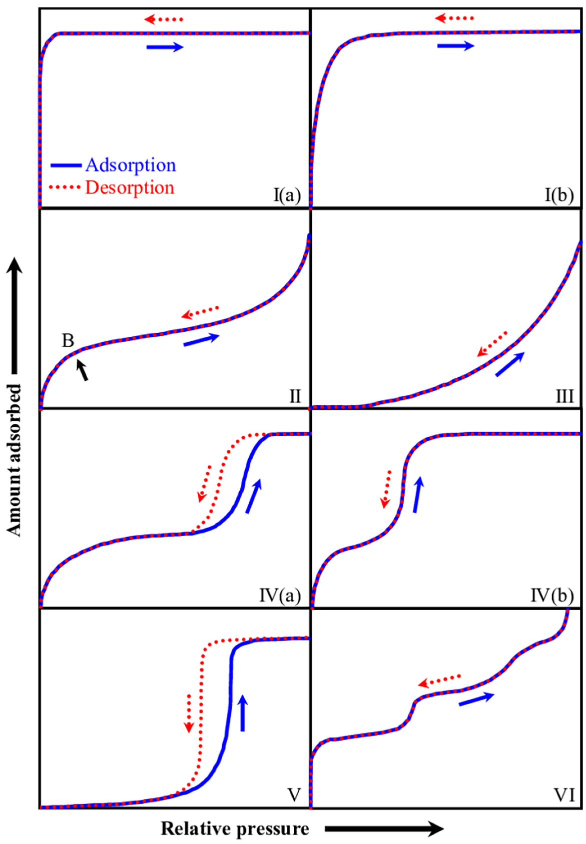

Figure 5. IUPAC classification of adsorption/desorption isotherms of N2 at 77 °K

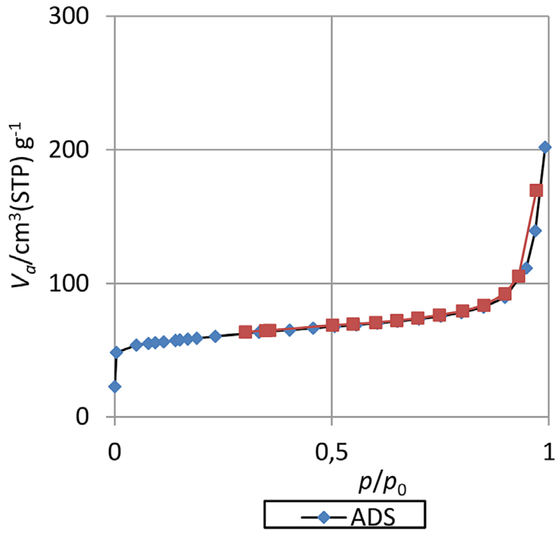

Figure 6. Adsorption/desorption isotherms of N_2 at 77 °K of [ZSM-5 (10)]

Fourier-transform infrared spectroscopy (FTIR)

The study of zeolite by infrared spectroscopy FTIR aims to determine the different chemical groups present on the surface of the catalysis. Primary building unit (PBU) of zeolites are tetrahedra linked by oxygen bridges and forming the so-called secondary building units (SBU). The spectrum of zeolites belonging to the structural groups was referred to the relationship between SBU type and vibrational spectrum. Spectra range were observed between (400–4000 cm^{-1}) as shown in Figure 7. The silicon (Si) or (Al) internal tetrahedral bending peak of the zeolite is assigned at 431 cm^{-1} and 447 cm^{-1} respectively.

Table 2. The results of surface area test

Sample code	SBET (m^2/g)	Pore volume (Vp) (cm^3/g)
10	259.58	0.3048

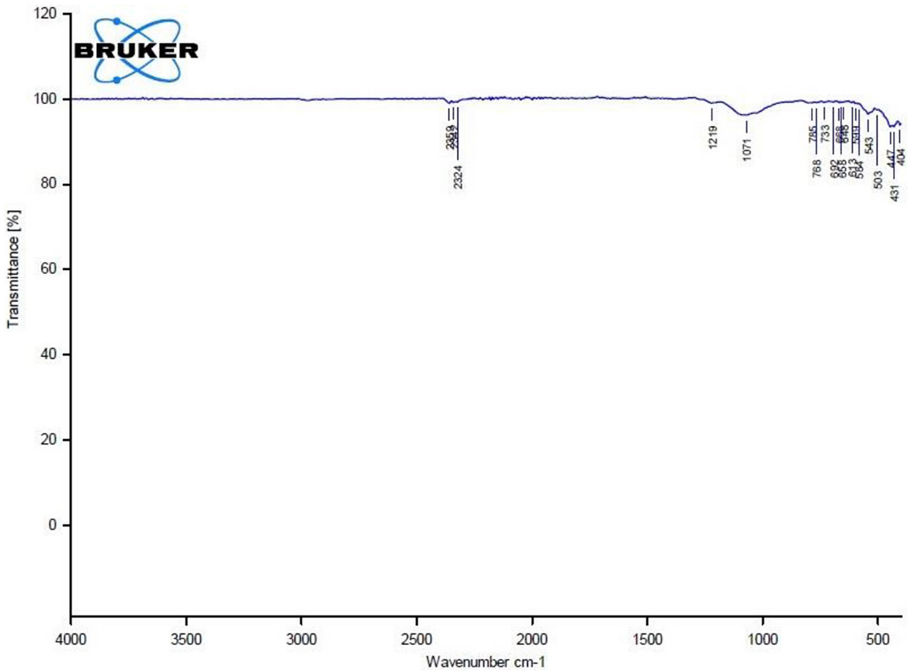

Figure 7. IR spectra of [ZSM-5 (10)]

The wavelength of 447 cm^{-1} is corresponding to the bending vibrations δ O-Si-O, occurring in "antiphase". While 543 cm^{-1} (complex band) symmetric stretching vibrations of bridge bonds νs Si-O-Si and bending vibrations δ O-Si-O. The double ring external peak is assigned at 584 cm^{-1} and 668 cm^{-1} symmetric stretching vibrations of bridge bonds νs Si-O-Al. The peak at 733 cm^{-1} symmetric stretching vibrations of bridge bonds νs Si-O-Si.

Symmetrical stretching external and internal linkage are assigned at 692 cm^{-1} and 768cm^{-1} respectively, while asymmetrical stretching internal and external are assigned at 1010 cm^{-1} and 1071 cm^{-1}. The peak around 3400 cm^{-1} is attributed to the hydroxyl group. The peak 1006 cm^{-1} asymmetric stretching vibrations of bridge bonds νas Si-O(Si) and νas Si-O(Al).

X-ray florescence

The quantitative chemical compositions analysis of the zeolite has been analyzed using XRF technique. The chemical composition in weight percent is listed in Table 3.

It can be seen that the percent of SiO_2 (81.688%) is dominant in all studied types of zeolites ZSM-5 (10), while the percent of Al_2O_3 (6.986%) is the second highest percentage. This various percentage of compounds is due to processing formulations and other production factors. The Si/Al ratio which has a clear contribution contrast of the morphology and characteristics of zeolites.

CRACKING OF HEAVY NAPHTHA

The heavy naphtha was analyzed by PIONA (paraffin, i-paraffin, olefin, naphthene, aromatic) according to ASTM D5134 standard. A gas chromatograph (MS-GC manufactured by Agilent) was employed to evaluate the reaction conversion. The catalytic cracking of heavy naphtha was performed with different parameters (Microwave power, preheating temperature, and flowrate) and Sio_2/Al_2O_3 ratio in ZSM-5 catalysts (10). The cracking of heavy naphtha compounds mostly represented by the conversion of paraffins to aromatics and olefins. The catalytic cracking reactions were performed with and without N_2 injection.

Table 3. The zeolite [ZSM-5(10) XRF analysis results]

SiO_2 %	Al_2O_3 %	Na_2O %	K_2O %	CaO %	MgO %	Fe_2O_3 %	TiO_2 %	SO_3 %	MnO %	P_2O_5 %	Cl %	LOI %
81.688	6.986	0.087	0.39	0.459	4.932	1.519	0.188	0.036	0.038	0.052	0.037	3.57

ZSM-5 (10) catalysts

The experimental design for the orthogonal array L9 (3^3) consists of nine design runs which give the most desired and best characteristics results as described in Tables (4 and 7). Statistical analysis combines the signal-to-noise (S/N) ratio and analysis of variance (ANOVA) for numerical analysis (Zisopol et al., 2022). Minitab's S/N ratio analysis is used to identify the optimum set of input parameters that will enhance conversion based on the functional characteristic. The usefulness of the biggest-is-best respond could be evaluated by applying the correlation presented below (Yudhanto et al., 2018):

Table 4. Conversion of paraffin of Taguchi's OA for zeolite ZSM-5 (10) without nitrogen injection

Preheating (A)	Microwave (B)	Flowrate (C)	Conversion
150	750	2	41.703
150	1000	4	49.587
150	1250	6	47.560
200	750	4	51.856
200	1000	6	54.090
200	1250	2	73.806
250	750	6	48.175
250	1000	2	61.354
250	1250	4	70.459

Larger is better: $SN_l = -10log\left(\frac{\sum_{i=1}^{n} 1/x_i^2}{n}\right)$ (1)

Two sets of experiments were performed with and without nitrogen injection. The control variables that were adopted for the experiments were the preheating temperature of heavy naphtha (A), the power of the microwave oven (B), and the flow rates of the heavy naphtha (C). The paraffin conversion after 12 minutes measure as response for Taguchi method to each set of control variables values in proposed orthogonal array (OA).

From Figure 8, it was concluded the interaction effect between preheating temperature, microwave power, and the flowrate as variables without nitrogen injection on the signal-to-noise ratios for the conversion of paraffin. The effect of increasing preheating temperature on conversion is positive. In general, the conversion increases as the preheat temperature increases up to 200 °C then the difference between A2 and A3 so small where the (S/N) value increased from 35.44% to 35.46. The effect of the increasing microwave power was positive between B1 and B2 where the (S/N) value of paraffin increased from 33.45% to 35.96%. In a reverse manner, the conversion decreases as the flow rate increases between C1 to C3. Precisely, the (S/N) value decreases from 35.17% to 33.95%

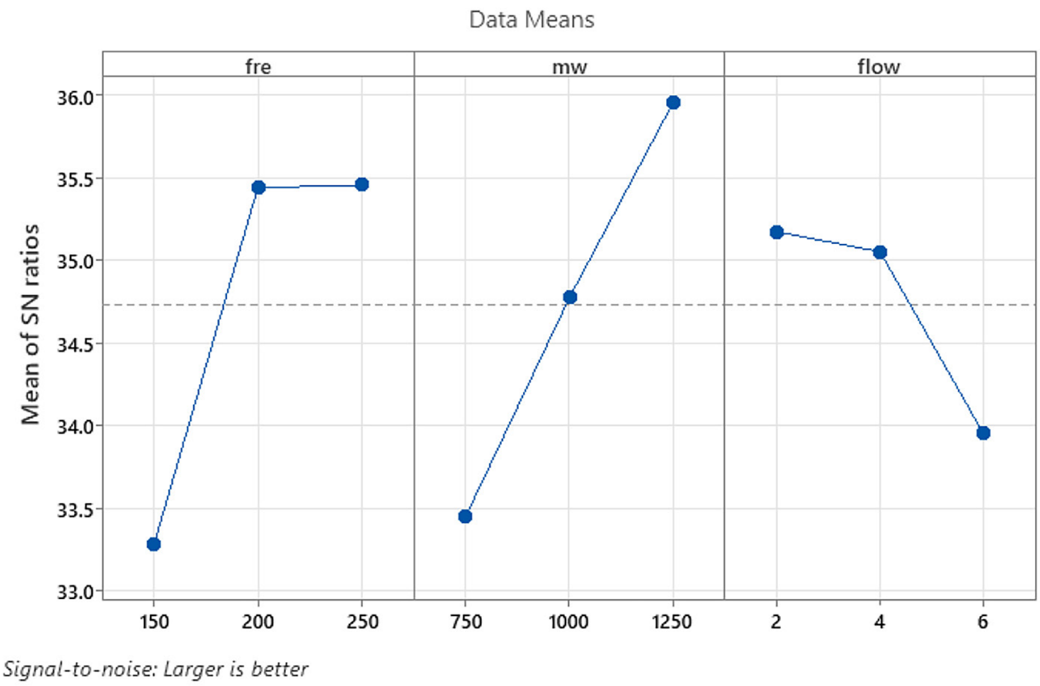

Figure 8. The signal to noise ratio for preheating, microwave power, and flow rate at zeolite ZSM-5 (10) without nitrogen injection

at the corresponding values of both the microwave power and the preheating temperature.

It is concluded that there is no optimum within the specific ranges of variables used in the experiments for this type of catalyst. There was always a maximum of at highest values of both preheating temperature and microwave power and the lowest value of flow rate.

Taguchi method in terms of responses parameter considered statistically significant if its p-value is below 0.05 (Eleiwi and Laleg-Kirati, 2014). Table 5 illustrates the signal-to-noise ratios results for conversion of Paraffin, where the maximum p value for flowrate regression was about 0.1, and the p values for preheating temperature and microwave power regressions were 0.032 (less than 0.05). This means that the preheating and microwave power in the regression Equation has a significant correlation with the response variables while flowrate had little effect on conversion. As shown in Tables 6, the most effecting factor is microwave power then preheating while flowrate has less effecting factor. This indication is agreed with p value (Table 5).

The mathematical expression for describing the system was got as multiple regression analysis for factors (A, B, and C) and interactions A × B, A × C, and B × C exhibit statistically significant effects on conversion. Equation 2 is polynomial Equation which represents the regression correlation of the controlled variables according to ANOVA analysis of the OA proposed by the Taguchi method.

$$Conv.\ \% = 21.04 - 0.29B - 3.96e^{-4}A + 23.43C + 4.80e^{-4}AB - 0.035BC - 0.017AC \quad (2)$$

The ANOVA calculations for conversion show that squared terms such as A × B, A × C, and B × C more significant than A, B, C factors alone. Model summary statistics showed that the excluding cubic polynomial model was aliased while quadratic model was found to have maximum (R^2) values. Equation 2 noted that the statistical significance was considered in the model based on analysis of variance. The R^2 value equals to 98.59% indicates a good fitting for the experimental data of conversion without nitrogen injection.

Figure 9 illustrates how the controlled variables (the preheating temperature, the microwave power, and the flow rate) affect the conversion of the paraffin using ZSM-5 (10) catalyst without nitrogen injection. In general, it is observed that the influence of the controlled variables has a monotonous effect on the cracking of naphtha represented as a conversion of paraffin in heavy naphtha, whether the effect is positive for preheating temperature and microwave power or negative for flowrate. This is previously approved according to the analysis of the signal to noise ratios (Fig. 8).

There is a maximum value for the conversion at the lowest value the flow rate and the highest values of both the preheating temperature and the microwave power. The associated figures, which represent the projections of the 3D form of the Equation, confirm this conclusion. The preheating temperature increased the conversion increased according to Arrhenius Equation all range of microwave power and flowrate, where the reaction conversion at preheating temperature (200 °C) and flowrate (6 l/hr) is (54%) and

Table 5. Analysis of variance for SN ratios at zeolite ZSM-5 (10)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Preheating	2	9.3620	9.3620	4.6810	30.55	0.032
Microwave	2	9.4087	9.4087	4.7044	30.71	0.032
Flowrate	2	2.7105	2.7105	1.3553	8.85	0.102
Residual error	2	0.3064	0.3064	0.1532		
Total	8	21.7876				

Table 6. Response table for signal to noise ratios (Larger is better) at zeolite ZSM-5 (10)

Level	Preheating	Microwave	Flowrate
1	33.29	33.45	35.17
2	35.44	34.78	35.05
3	35.46	35.96	33.95
Delta	2.17	2.50	1.22
Rank	2	1	3

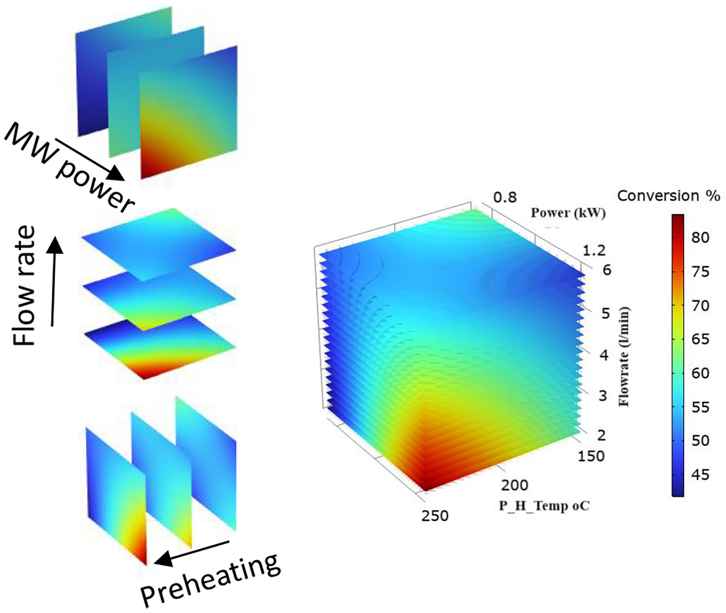

Figure 9. 3D representation and the projections of a regression Equation 2

(61.3%) at preheating temperature (250 °C) and flowrate (2 l/hr) for same microwave power.

The reaction conversion is proportional to the period of reaction so, the conversion decreased with increasing of flowrate (less residence time) because of the hydrocarbons molecule of naphtha have longer residence time in the activity zone by reduce flowrate that can be seen in Figure 9. Therefore, increase flowrate led to less opportunities to reaction. Generally, the conversion is significantly influenced by the flow rate, preheating temperature and the applied microwave power, so the design must take into account the applied power per unit of feed, resulting in reduced costs and energy consumption.

In order to assess the influence of microwave power, the experiments were performed within the range (750 to 1250) W and the reaction conversion directly proportional to the microwave power conversion. Figure 9 shows that the maximum percentage of cracking (73.8%) occurs at a microwave power of (1250 W), a flowrate of (2 l/hr) and (200 °C).

The microwave produced enough energy for cracking process to proceed even at low temperatures because generate "hotspots" that highly increase the reaction rate. "Hot-spot" generation between catalyst particle where the electric field intensity is much greater at contact spots between catalyst particles which generate concentrated electric field leads to the formation of higher-temperature areas or hotspots. The temperature gradient between the bulk of catalyst and vicinal spots is affected by thermal conductivity of the catalysts. The hotspots size is ranging from 90 to 1000 micrometres due to the electromagnetic fields. The temperature difference between the bulk and the hotspots could be varied from 15 to 200 °C. A greater amount of energy will cause the increasing of chemical bonds vibration and increased intensity and leads to the bonds breaking. So, the characteristics of heavy naphtha cracking can be enhanced by converting heavy hydrocarbon molecules into lighter ones and cracks polar molecules.

From Table 7 could be found that all the reaction conversion of paraffin with nitrogen injection are higher than the reaction conversion of paraffin without nitrogen injection in all conditions investigated due to velocity increase which offer more mobility of molecules and then more contact with catalyst.

Figure 10 explain the conversion of paraffin represented by (S/N) ratio with nitrogen injection, the (S/N) ratio increased with preheating increasing, where (S/N) ratio is 33.2 at A1 and 36 at A2, while it behaves differently between A2 to A3, surprisingly it decreased with increasing preheating ((S/N) ratio is 36 at A2 and 35.4 at A3). Microwave power increasing lifted reaction conversion represented by (S/N) ratio 32.94 at B1 to 36.34 at B3. Initially the (S/N) ratio increased with increasing flowrate, where (S/N) ratio is 35.2 at C1 to 35.3 at C2 then subsequently decreased with flowrate increasing from (35.3 at C2 to 34.1 at C3) as a result of interacting factors.

Table 7. Conversion of paraffin of Taguchi's OA for zeolite ZSM-5 (10) / with nitrogen injection

Preheating (A)	Microwave (B)	Flowrate (C)	Conversion
150	750	2	38.2937
150	1000	4	50.9734
150	1250	6	49.1104
200	750	4	52.7815
200	1000	6	60.6846
200	1250	2	77.5640
250	750	6	43.1541
250	1000	2	64.1591
250	1250	4	74.1636

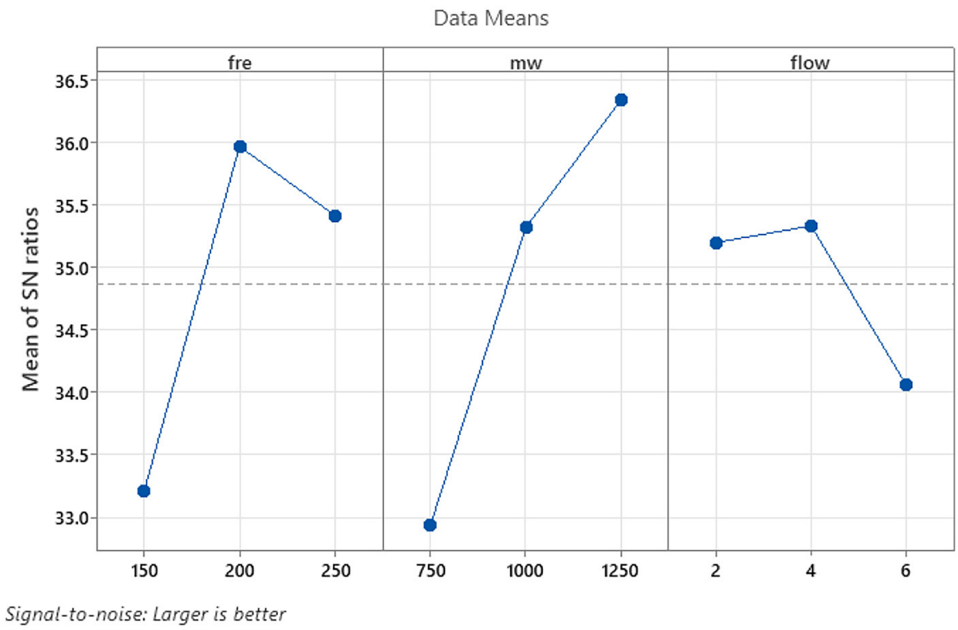

Figure 10. The trend for preheating, microwave power, and flow rate at zeolite ZSM-5 (10) with nitrogen injection

The optimization analysis gives optimum values for preheating temperature and flowrate.

Table 8 illustrates the analysis of (S/N) ratio results which indicate good correlation due to small p values (less 0.05). the p values for preheating and power of microwave (0.001) are better than p value for flowrate (0.006). This means that, most influencing factors are preheating and power in the regression Equation because they have significant correlation with the response while flowrate less influencing effect on conversion because p value be more effective when diminished toward zero. Tables 9 show the gradual descending effect of influencing factors on conversion from microwave power then preheating and last effecting factor is flowrate. This gradual ascending effect is correspondent with p value. The interactions of factors in the mathematical expression have more significant effects on conversion than single factors. The mathematical model is presented by (ANOVA) as follows:

$$Conv.\ \% = 32.6024 - 0.54311B - 5.51e^{-2}A + \\ + 45.24C + 9.3e^{-4}AB - 9.3e^{-2}BC - 2.6e^{-2}AC \quad (3)$$

The set of experiments with nitrogen injection have a good fitting with high precision of reaction conversation data ($R^2 = 99.35\%$)

Using catalyst type ZSM-5 (10) with nitrogen injection, Figure 11 shows the relationship between the reaction conversion and (preheating temperature, microwave power, and flow rate) by 3D projections form. The reaction conversion represented by 3D projections form and split sheets could illustrate the relationship between all factors as single factors and interacting factors

Table 8. Analysis of variance for SN ratios at zeolite ZSM-5 (10) with nitrogen injection

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Preheating	2	12.7706	12.7706	6.38532	751.64	0.001
Mw	2	18.2889	18.2889	9.14443	1076.42	0.001
Flow	2	2.9308	2.9308	1.46542	172.50	0.006
Residual error	2	0.0170	0.0170	0.00850		
Total	8	34.0073				

Table 9. Response table for signal to noise ratios (Larger is better) at zeolite ZSM-5 (10)

Level	Preheating	mw	Flow
1	33.21	32.94	35.20
2	35.97	35.32	35.33
3	35.42	36.34	34.06
Delta	2.76	3.40	1.27
Rank	2	1	3

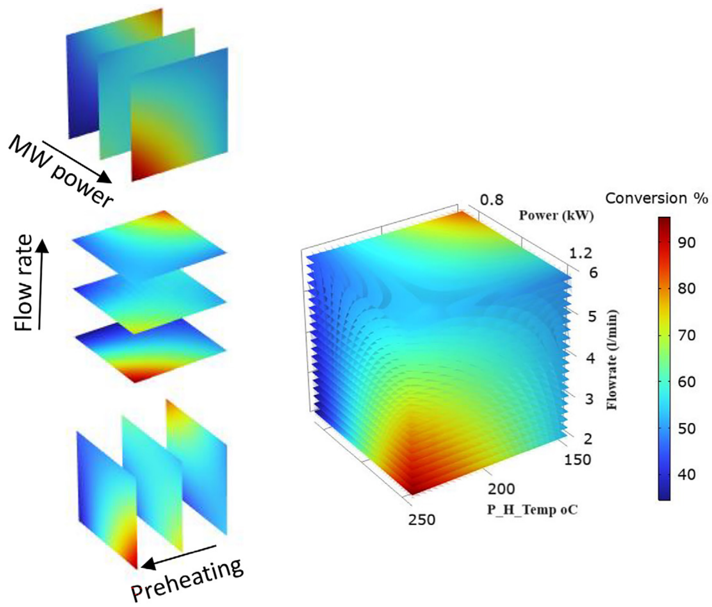

Figure 11. 3D representation and the projections of a regression Equation 3

with factorial relationship. Also signal to noise ratios are function of studied factors could be found in Figure 10.

From Figures (8, 10) noted that the (S/N) ratios increased with increasing of preheating temperature and microwave power and decreasing with flowrate increasing in set of experiment without nitrogen injection while it has optimum point for the preheating temperature and flowrate (35.97, 35.32) respectively in set of experiment with nitrogen injection. The (S/N) ratios are higher with nitrogen than without nitrogen in all conditions. It could be related to increase the mobility of molecules and then increase the contact of molecules of catalyst (conversion increase). The flow of nitrogen through the experiment activates the catalyst (Senise et al., 2011).

The preheating temperature in sets of experiment with nitrogen have optimum value while it is increasing in sets of experiment without nitrogen because the catalyst destroyed by high temperature. The effect of flow rate in sets of experiment with nitrogen is increasing the contact of molecules with the catalyst due to increase mobility of molecules up to (4 l/hr) then the reaction conversion decreased. The first range of flowrate offer enough time of contact and mobility of molecules while the second range of flowrate increase the mobility but don't affect enough time for contact (less residence time). Microwave power always increase the reaction conversion because it provides the required activation energy for the cracking process. The maximum conversion is (77.56%) at microwave power of (1250 W), a flowrate of (2 l/hr) and preheating temperature (200 °C) (Fig. 11).

CONCLUSIONS

The catalytic process enhanced with microwave power increase the reaction conversion at lower temperature than the conventional methos. The injection of nitrogen improves the reaction kinetics. The microwave energy generates hot spots which provide best conditions for process completion with lower energy. The best result of cracking reaction conversion is (77.56%) at microwave power of (1250 W), a flowrate of (2 l/hr) and preheating temperature (200 °C). it was noted that the flowrate has no effect on in the range (2–4 l/hr). all the traditional processes can not crack the heavy naphtha in the range of (150–250 °C). The experiment of microwave technique could be scaled up to be mass production unit in any refinery.

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