



## Research Article

# Optimization of Oxidative Desulfurization Reaction with $\text{Fe}_2\text{O}_3$ Catalyst Supported on Graphene Using Box-Behnken Experimental Method

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## Abstract

In this study, the catalyst activity of  $\text{Fe}_2\text{O}_3$  supported on Graphene for Iraqi gas oil oxidation desulfurization (ODS) by hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) was investigated. The prepared catalyst was synthesized by wet impregnation for ferric nitrate as a  $\text{Fe}_2\text{O}_3$  precursor while Graphene represented as catalyst support. The synthesized catalyst was characterized by XRD, FTIR, and EDS analysis. The experiments were designed according to three-level for three variables by Box-Behnken experimental design; Stirring time, catalyst dosage and temperature while the sulfur removal efficiency acts as experiment response. Catalyst activity was studied by ODS reaction for Iraqi gas oil (sulfur content 9400 ppm) at temperature range (40-60 °C), stirring time (160-240 minutes) and catalyst dosage (0.5-2.5 g), the results show maximum sulfur removal efficiency 90% at stirring time, catalyst dosage and temperature 240 min, 1.5 g, and 60 °C, respectively. ANOVA analysis shows the important effect of each independent variable on sulfur removal efficiency (response) as following influential order; stirring time, reaction temperature and catalyst dosage. Kinetics calculation showed that the ODS reaction obeys pseudo first-order reaction with reaction rate constant equal 1.0837, 1.5893, and 2.5053 at temperature 40, 50, and 60 °C, respectively, while activation energy equal 36.26 kJ/mol. Copyright © 2020 BCREC Group. All rights reserved

**Keywords:** Oxidative desulfurization; ODS; Graphene; Design experiment; Box-Behnken; ANOVA

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## 1. Introduction

Generally, raw gas and oil contain an amount of sulfur as impurities. Owing to environmental concerns, human health issues, and corrosion problems, many restrictions introduce to remove or reduce the sulfur content. Sulfur

considers the precursor elements in the process of acid rain formation by consisting of sulfur oxide [1]. Besides, the presence of sulfur causes corrosion in the refineries facilities, reforming catalysts poisoning and undesirable odors [2]. The conventional method for sulfur removing from petroleum fractions is catalytic hydrodesulfurization. Hydrodesulfurization process (HDS) suggests using a suitable catalyst, usually, the sulfide of (Molybdenum, Mo; Tung-

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sten, W) promoted by (Nickel, Ni; Cobalt, Co) at high temperature and high hydrogen partial pressure supported on proper carrier comes with an active surface area like Alumina [3]. However, hydrodesulfurization is inefficient for removing some of the sulfur compounds in oil like heterocyclic sulfur compounds, benzothiophene and dibenzothiophene [4,5]. In 2005, the European community and USA limits sulfur contents in motor fuels to 40-50 ppm, while Germany limits the sulfur level to around 10 ppm since 2001 [4]. Hao *et al.* mentioned that many countries have released very strict regulations in regard to sulfur contents to be around 10 ppm [6]. This ultra-low sulfur considers as a real challenge for the traditional hydrodesulfurization process. Where the HDS process needs harsh operating conditions to remove a large amount of sulfur which resulting in reducing the quality of fuels. Therefore, alternative technology is required for high capacity sulfur removal that can be effective to reach these new regulations.

The oxidative desulfurization (ODS) is a promising process for deep desulfurizing from petroleum fractions which can be carried out with mild operation conditions like room temperature and atmospheric pressure [5-6]. In comparison to the hydrodesulfurization process, the oxidative desulfurization process can be presented with temperature below 80 °C, high selectivity, and no expensive hydrogen. In terms of cost, HDS is more expensive than ODS due to high hydrogen pressure requirements for kinetic and catalyst stability purposes [7,8]. Several oxidation agents applied in ODS processes such as ozone, hydrogen peroxide, peracids and tertbutylhydroperoxide [9]. Among these agents, peroxides are very attractive due to their high reactivity and selectivity under mild operation conditions. The oxidation reaction can be done in non-acidic media, in existence of catalysts such as tungsten, vanadium or molybdenum supported on zeolite, silicates, molecular sieves, *etc.* [10]. The oxidative desulfurization process consists of two stages; first stage oxidation of sulfur compounds to forms

have high polarity and the following stage is removing of oxidized sulfur compounds to present clean fuels [8,9]. Many researchers investigated applying various catalysis, like Cu, Ti, Cr, Mn, Fe, Co, W, and V, which are known as transition metal oxides [9]. Besides, the oxidation desulfurization process has been studied using various reactions like hydrogen peroxide-formic acid, hydrogen peroxide-acetic acid, hydrogen peroxide-polyoxometalates, ozone, and photooxidation with molecular oxygen in the presence of sensitizers, such as: cyanoarenes [9]. Among all these reactions, the oxidation of DBT and its derivatives with hydrogen peroxide in acidic media considers as an attractive reaction due to that reaction carried out under ambient conditions and its high selectivity. Correspondingly, the use and the store of these peroxides on large scale considers dangerous. Figure 1 shows the common reaction of DBT oxidation by hydrogen peroxide in acidic media, in which sulfoxides and sulfones can be removed easily with an appropriate solvent as extract [10].

In this study, the catalyst activity of Fe<sub>2</sub>O<sub>3</sub> supported on Graphene for Iraqi gas oil oxidation desulfurization (ODS) by hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) was investigated. This piece of work examines the sulfur loading on the Fe<sub>2</sub>O<sub>3</sub> catalyst supported on graphene synthesized for ODS reaction to remove sulfur compounds from Iraqi gas oil. Where the study carried out using Box-Behnken experimental design method with three-level variables. The maximum reachable of sulfur removal efficiency was 90%. Analysis variation study using ANOVA has been performed to investigate the impact of various parameters on the sulfur removal efficiency like stirring time, reaction temperature and catalyst dosage.

## 2. Materials and Methods

### 2.1 Materials

Iraqi gas oil with sulfur content (9400 ppm) provided from Najaf refinery, graphene prepared from dehydration of Iraqi date syrup described by Makki & Alwan [11]. Analytical grade chemicals reagents used in this study hydroxide peroxide H<sub>2</sub>O<sub>2</sub>, ferric nitrate (Fe(NO<sub>3</sub>)<sub>3</sub>·9H<sub>2</sub>O), glacial acetic acid (CH<sub>3</sub>COOH), sodium bicarbonate (NaHCO<sub>3</sub>), sodium carbonate (Na<sub>2</sub>CO<sub>3</sub>), nitric acid (HNO<sub>3</sub>), sulfuric acid (H<sub>2</sub>SO<sub>4</sub>), Acetonitrile (CH<sub>3</sub>CN).



**Figure 1.** Oxidation desulfurization process of DBT [10]

### 2.2 Catalyst Preparation and Characterizations

The proposed catalyst is ferric oxide Fe<sub>2</sub>O<sub>3</sub> supported on graphene and it was synthesized by wet impregnation method. Graphene surface functionalized by pouring into a mixture of concentrated sulfuric acid and nitric acid at 50 °C under the sonication condition for 2 hours. Next, washing graphene with distilled water to removed acidic trace and filtration. Finally, functionalized graphene dried at 110 °C for 4 hours' duration under vacuum. Ten grams of functionalized graphene poured into three necks round bottom which immersed in an ultrasonic bath and connected to vacuum a pump for moisture removal. Specific amounts of ferric nitrate (Fe(NO<sub>3</sub>)<sub>3</sub>·9H<sub>2</sub>O) dissolved in distilled water and added to functionalized graphene drop by drop to produce catalyst contains 10 wt.% of Fe<sub>2</sub>O<sub>3</sub> on graphene. During the impregnation step adding sodium bicarbonate (1 M) solution at pH range 8-9 as a precipitation agent for getting good precipitation. The impregnated catalyst dried at 100 °C for a single night and calcined at 450 °C for 4 hours.

Fourier - Transform Infrared Spectroscopy (FTIR) spectra abstained on BRUKER Model PLATINUM-ATR Alpha series Germany over range 4000-400 cm<sup>-1</sup> at room temperature. X-ray diffraction (XRD) pattern was got on Shimadzu Model XRD- 6000 Japan, while Energy Dispersive X-ray Spectrometry (EDS) maps done on BRUKER Model X Flash 6110 Germany which attached with scanning electron microscope (SEM) FEI model QUANTA 450.

**Table 1.** Independent (controllable) variables and their levels.

Variables, unit	Symbol		Levels		
	Coded	Actual	-1	0	1
Stirring time, min	$x_1$	$X_1$	160	200	240
Catalyst dosage, g	$x_2$	$X_2$	0.5	1.5	2.5
Temperature, °C	$x_3$	$X_3$	40	50	60

**Table 2.** Box-Behnken design matrixes.

Run	Design Parameters			Run	Design Parameters			Run	Design Parameters		
	$x_1$	$x_2$	$x_3$		$x_1$	$x_2$	$x_3$		$x_1$	$x_2$	$x_3$
1	-1	0	1	6	0	-1	1	11	0	1	1
2	0	0	0	7	1	-1	0	12	0	-1	-1
3	0	0	0	8	1	1	0	13	-1	-1	0
4	0	0	0	9	1	0	1	14	-1	1	0
5	0	1	-1	10	1	0	-1	15	-1	0	-1

### 2.3 Oxidative Desulfurization Procedure

The oxidative desulfurization ODS process investigated under the effect of following independent variables; reaction temperature, stirring time (period of batch), and weight of catalyst dosage arranged according to Box-Behnken experimental design. The oxidation process starts by heating 100 ml of gas oil using the magnetic stirrer heater to reach the required temperature, 10 mL of hydrogen peroxide, 5 mL of glacial acetic acid with the required weight of catalyst added to gas oil. The stirring continues for the designed time following the Box-Behnken matrix, in which the reaction stopped by adding sodium carbonate solution (2 g dissolved in 20 mL distilled water) after the required time [12]. After the oxidation reaction, oxidized sulfur extracted using acetonitrile at the ambient temperature where the oil phase separated. The loading capacity of sulfur measured by X-ray fluorescence (Sulfur Meter model RX-620SA/Tanka Scientific) and total sulfur removal efficiency calculated according to Equation (1).

$$SR\% = \frac{S_0 - S_f}{S_0} \times 100 \quad (1)$$

where, SR% is sulfur removal efficiency,  $S_0$  denotes sulfur in raw oil, and  $S_f$  is sulfur after oxidation.

### 2.4 Design of Experiment

Response Surface Methodology (RSM) is a mathematical and statistical method collection that is useful to model and analyze engineering problems as well as it can be used as an optimization technique to evaluate the correlation between observed experimental responses with controllable variables [13]. The Box-Behnken method is one of the most RSM methods used for the design of experimental and it can be described as a central -composite design CCD. Box-Behnken design method has the ability to study experiments with a possible minimum

number of experiments with a high degree of accuracy compared with classical methods. The number of experiments required to cover the variables range was established according to the Box-Behnken matrix which is determined by Equation (2) [14].

$$N = 2k(k-1) + r \quad (2)$$

Where  $N$  is the number of experiments,  $k$  is the number of variables, and  $r$  is the replicate number of central points (3-6).

The method stated that variables levels adjusted at only three levels (-1, 0, +1) and intervals between these levels are equal. For three variables Box-Behnken design the total number of experiments that determined by Equation (2) are 12 plus three replicate numbers of central points and the total will be 15 experiments to estimate the effects of independent variables on the oxidation process. Compared to Box-Wilson experimental design method needs 27 runs to cover three independent variables system.

Table 1 shows  $X_1$ ,  $X_2$ , and  $X_3$  the actual variables (factor) chosen for this design with three levels low (-1), intermediate (0), and high (+1) values. The coded variables ( $x_1$ ,  $x_2$ , and  $x_3$ ) were related to actual variables by Equation (3).

$$x_i = \frac{X_i - X_0}{\Delta X_i}; \quad i = 1, 2, 3 \quad (3)$$

Where  $X_0$  is real value for the independent variable at the center level, and  $\Delta X$  is the interval value. Table 2 shows the matrixes for Box-Behnken was for optimization of the oxidation

desulfurization process in terms of estimation of the effects of stirring time, catalyst dosage, and reaction temperature on the sulfur removal efficiency, the experimental observation arranged at random orders [13].

The observed results for the effects of Stirring time, catalyst dosage, and reaction temperature on oxidative desulfurization can be fitted as second-order polynomial by the aim of Design-Expert software, and it can be used to predict optimum point, for three variables where the second-order polynomial represents by Equation (4) [15].

$$y = \beta_0 + \sum \beta_i x_i + \sum \beta_{ii} x_i^2 + \sum \beta_{ij} x_i x_j + \varepsilon \quad (4)$$

Where  $y$  is predicated response,  $\beta_0$  is the intercept coefficient,  $\beta_i$  is the linear effect (slope) of input variable  $x_i$ ,  $\beta_{ij}$  is interaction effect of linear by linear between two input variables  $x_i$ , and  $\beta_{ii}$  is squared effect.

Analysis of Variance ANOVA is a statistical method to decision-making for the purpose of detecting the differences in the rate of performance of the variables examined, where the sum of squares and F-statistics are used to know the relative importance of processing data analyzed and measurement of errors and uncontrolled parameters.

### 3. Result and Discussion

#### 3.1 Characterization of Prepared Catalyst

X-ray diffraction (XRD) patterns show significant peaks at  $2\theta = 35.52^\circ$ ,  $52.98^\circ$ , and  $62.09^\circ$

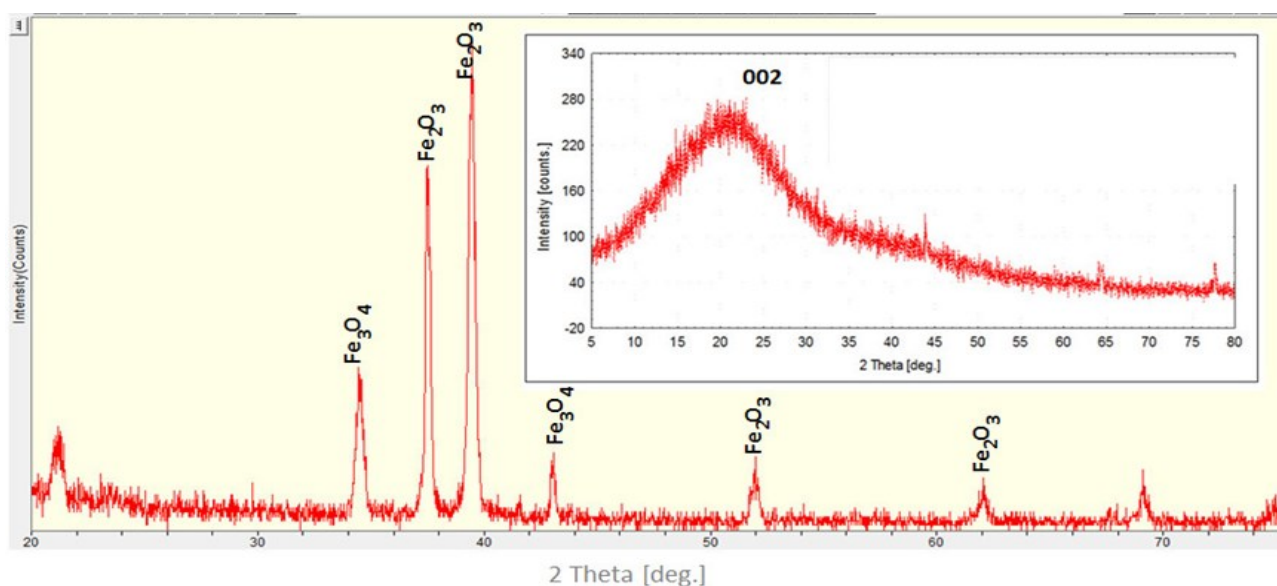


Figure 2. XRD pattern for Fe<sub>2</sub>O<sub>3</sub>/Graphene catalyst. Inset pattern shows XRD pattern for Graphene prepared from Iraqi date syrup [11].

which referred to  $\text{Fe}_2\text{O}_3$  (hematite) and  $\text{Fe}_3\text{O}_4$  (magnetite) while the peaks at  $2\theta = 33.89^\circ$ ,  $39.47^\circ$ , and  $43.07^\circ$ , this agrees with Ugal *et al.* work [12]. In addition, the XRD pattern shows a small peak around  $2\theta = 28.9^\circ$  which refers to disordered amorphous sheets of Graphene for iron/Graphene nano-composites and this shows good agreements with Lima *et al.* findings [16]. The average crystal size calculated by Scherrer formula using full-width at half maximum (FWHM) at a stronger diffraction peak, where

the average crystal size found to be  $7.14 \text{ \AA}$ . The inset figure in Figure 2 is for prepared Graphene, it shows wide peak centered at  $2\theta = 23.758^\circ$  for plane (002) with  $d$ -spacing  $d_{002} = 3.742 \text{ \AA}$  ( $0.374 \text{ nm}$ ) and this is agree with [17,18].

FTIR spectrum used to identify functional groups within the sample in sample; the broad peak at about  $3406 \text{ cm}^{-1}$  is ascribed as vibration for bonded OH group. The bond at  $1200 \text{ cm}^{-1}$  and  $1620 \text{ cm}^{-1}$  due to C-H and C=C aro-

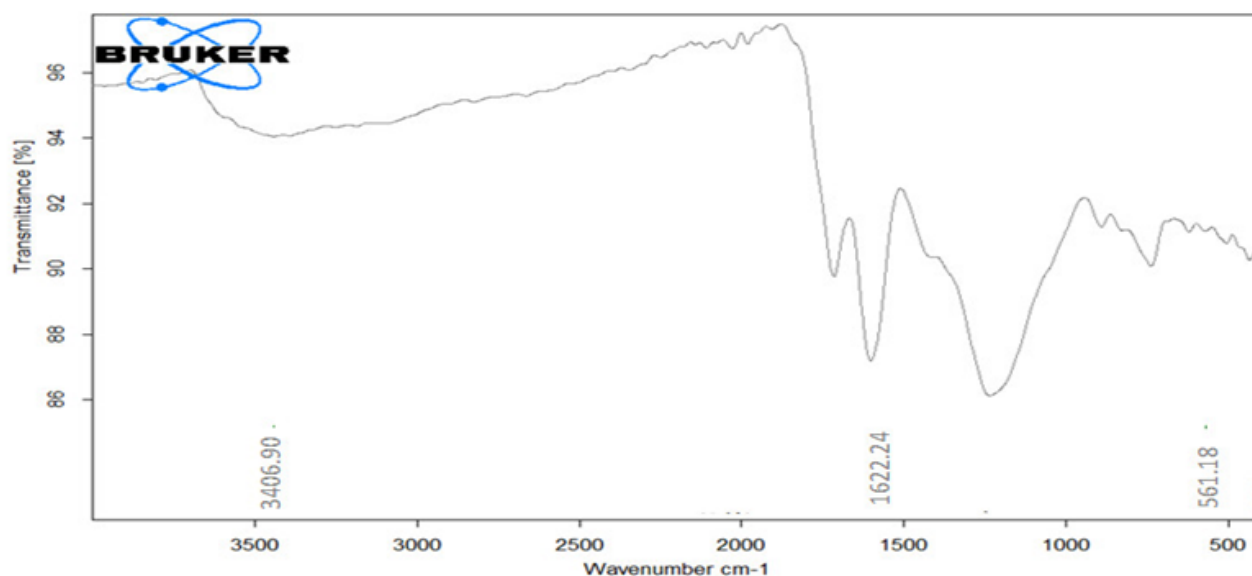


Figure 3. FTIR spectra for  $\text{Fe}_2\text{O}_3$ /Graphene catalyst

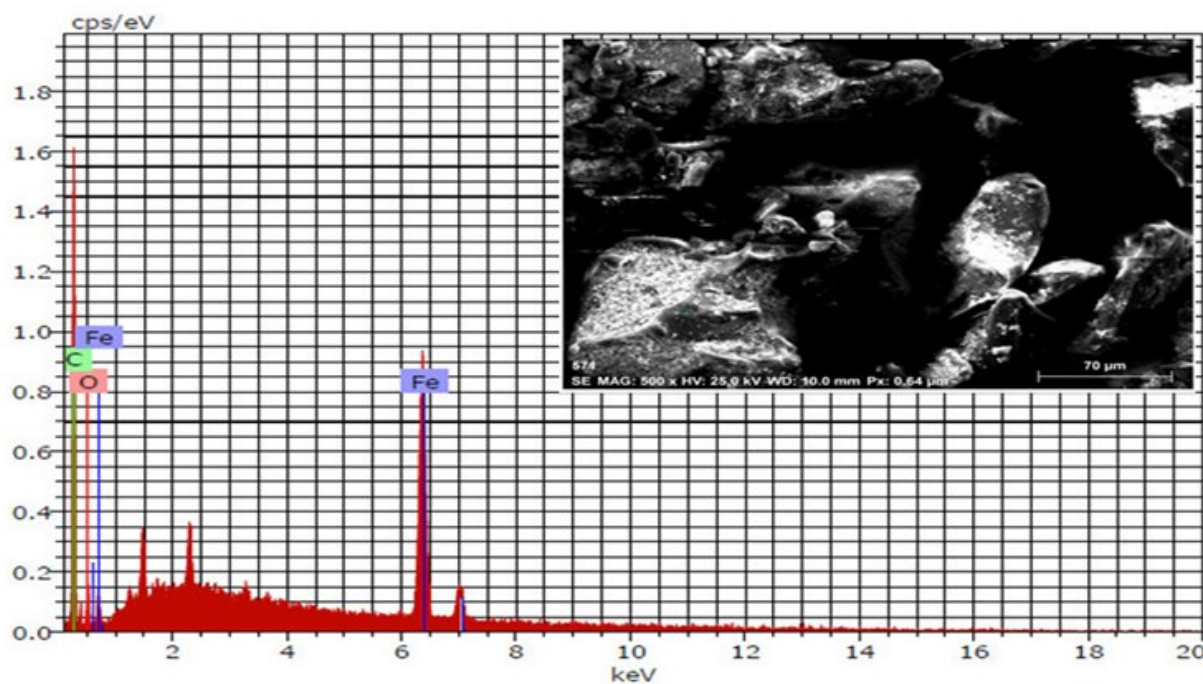


Figure 4. EDS analysis (elements mapping) for prepared catalyst. Inset shows the SEM image for catalyst.

matic, while the peak at about 560 cm<sup>-1</sup> represents Fe-O vibration. In addition, the possible reason behind the vibration between about 1600-1200 cm<sup>-1</sup> is that as a complexes formation either for bidentate or monodentate which comes from the carboxyl group with iron as shown in Figure 3. EDS analysis refers to the presence of iron and oxygen as well as the support (carbon) Figure 4.

### 3.2 Results of the Oxidation Desulfurization Reaction

Table 3 shows the sulfur content in final product measured for all the 15 experiments

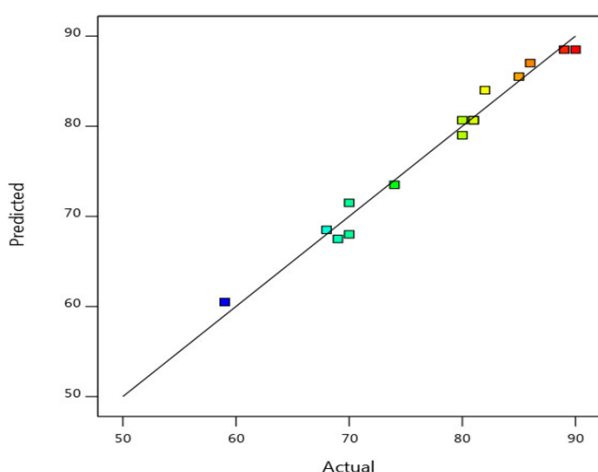


Figure 5. Experimental and predicted response plot.

and the sulfur removal efficiency, as well as, the sulfur removal efficiency using Equation (5). Experiments results fitted as a second-order polynomial (quadratic model) with Box-Behnken design and by the aim of Design-Expert software version 11. The relationship between sulfur removal efficiency and independent variables based on the fitting results shown in Equation (5).

$$y = 80.67 + 8.0x_1 - 2.0x_2 + 6.0x_3 - 0.5x_1x_2 + 2.5x_1x_3 + 3.5x_2x_3 - 4.58x_1^2 + 2.58x_2^2 - 4.08x_3^2 \quad (5)$$

The analysis of variance results for the predicted model shown in Table 4, by the aim of Design-Expert software, which shows a good fitting data for the second-order (quadratic) model. ANOVA analysis shows that *F*-value is 29.11 for regression which is greater than the tabulated value from the standard distribution table Fisher's *F*-test value obtained, (*F*<sub>9,5,0.05</sub> = 4.77). The high R<sup>2</sup> (0.9813) indicates that the assumed model is reasonably well-fitting with actual data. The experimental points are very little diverging from the points that predicted by the quadratic model (Equation (5)) which illustrated graphically with 45° line as shown in Figure 5 which indicate again a good fitting for the suggested model. Low *P*-value (*P* < 0.05) referred the parameter in the suggested model is statistically highly significant. In this work, the terms of *x*<sub>1</sub>, *x*<sub>2</sub>, *x*<sub>3</sub>, *x*<sub>2</sub>*x*<sub>3</sub>, *x*<sub>1</sub><sup>2</sup>, *x*<sub>2</sub><sup>2</sup>, and *x*<sub>3</sub><sup>2</sup> are significant parameters because of their values

Table 3. Experimental (observed) and predicted sulfur removal efficiencies at different conditions

Run	Coded Variables			Actual Variables			Response S%	
	<i>x</i> <sub>1</sub>	<i>x</i> <sub>2</sub>	<i>x</i> <sub>3</sub>	Reaction time	Catalyst dosage	Temperature	Experimental	Predicted
1	-1	0	1	160	1.5	60	69	67.51
2	0	0	0	200	1.5	50	81	80.67
3	0	0	0	200	1.5	50	80	80.67
4	0	0	0	200	1.5	50	81	80.67
5	0	1	-1	200	2.5	40	70	68.01
6	0	-1	1	200	0.5	60	82	84.01
7	1	-1	0	240	0.5	50	89	88.51
8	1	1	0	240	2.5	50	85	85.51
9	1	0	1	240	1.5	60	90	88.51
10	1	0	-1	240	1.5	40	70	71.51
11	0	1	1	200	2.5	60	86	87.01
12	0	-1	-1	200	0.5	40	80	79.01
13	-1	-1	0	160	0.5	50	74	73.51
14	-1	1	0	160	2.5	50	68	68.51
15	-1	0	-1	160	1.5	40	59	60.51

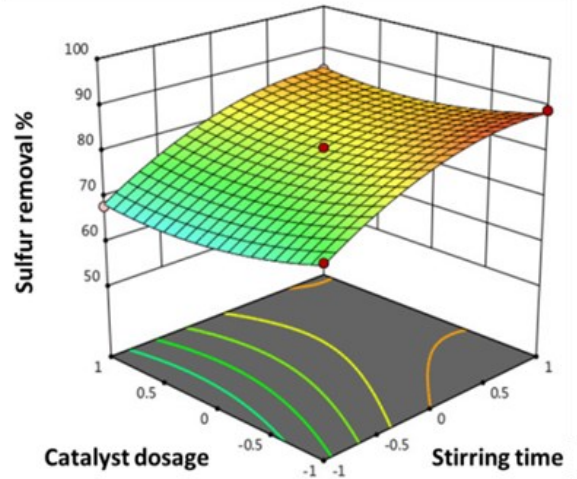
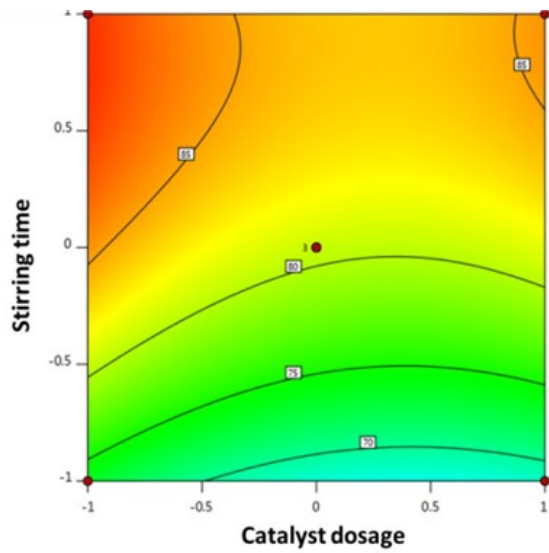


Figure 6. 2-D and 3-D plot of sulfur removal efficiency vs stirring time and catalyst dosage.

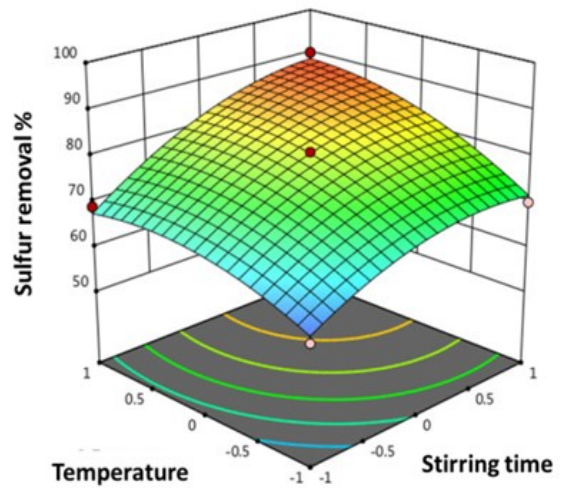
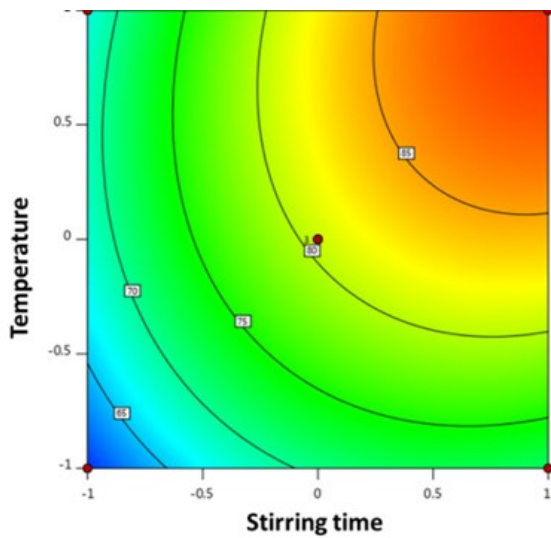


Figure 7. 2-D and 3-D plot of sulfur removal efficiency vs stirring time and temperature.

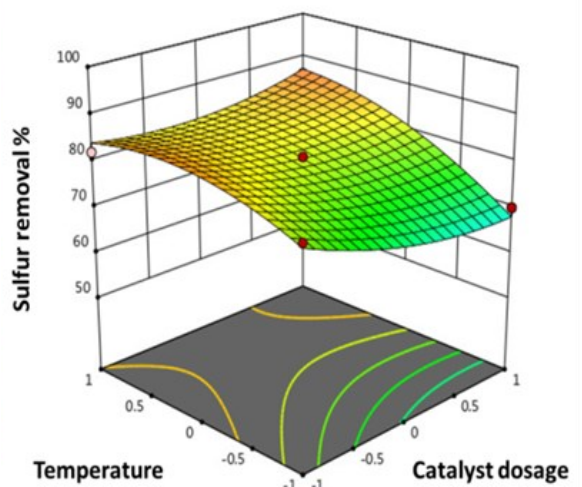
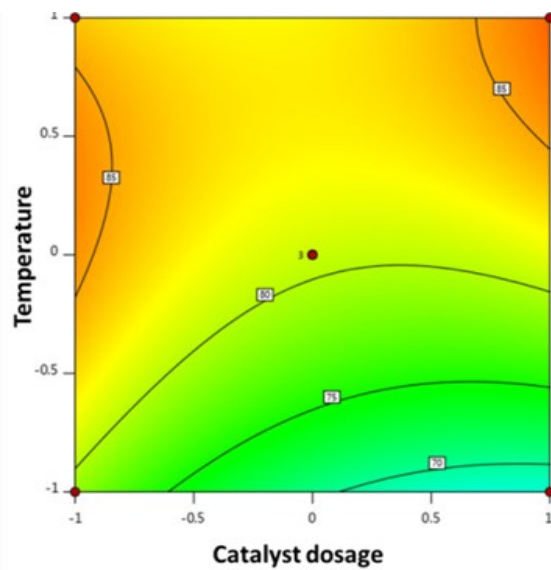


Figure 8. 2-D and 3-D plot of sulfur removal efficiency vs temperature and catalyst dosage.

are less than 0.05. Meanwhile, *P*-value for the term of  $x_1x_2$  is not significant via its value larger than 0.05 and  $x_1x_3$  is slightly significant because its *P*-value is slightly larger than 0.05, that lead rewrite Equation (5) as below in Equation (6).

$$y = 80.67 + 8.0x_1 - 2.0x_2 + 6.0x_3 + 2.5x_1x_3 + 3.5x_2x_3 - 4.58x_1^2 + 2.58x_2^2 - 4.08x_3^2 \quad (6)$$

Based on the results, stirring time shows the highest effect on the sulfur removal efficiency followed by the temperature of reaction and catalyst dosage as predicated according to their *F*-value 123.87, 69.68, and 7.74, respectively listed in ANOVA results in Table 4. Generally, reactions require time for completion, and it is clearly visible that sulfur removal efficiency initially increasing with reaction time to

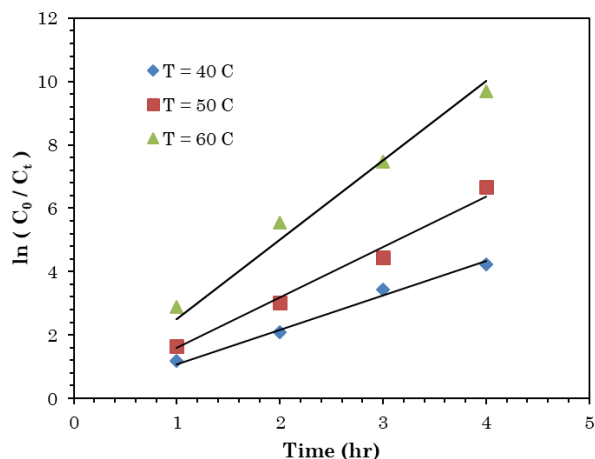


Figure 10. The plot of  $\ln (C_0/C_t)$  vs time at studied temperature.

a specific time, then marginally decreased. The possible reason behind this is the interaction between  $H_2O_2$  (oxidizing agent) with sulfur components due to the losses in the oxidation agent with time.

The interactive effect of each two independent variables on sulfur removal efficiency was determined by illustrating response (sulfur removal efficiency) as two dimensional (2D) and three dimensional (3D) plots. As shown in Figure 6, temperature was kept at 50 °C while catalyst dosage and stirring time were kept constant at 1.5 g and 200 minutes, respectively. Noticeably, sulfur removal efficiency varies with stirrer time to a great extent compared to catalyst dosage.

Figure 7 shows the effects of the temperature of reactions and stirring time on the sulfur efficiency. The results illustrate that increases both variables result in increasing sulfur removal efficiency. On the other hand, Figure 8 represents the effect of temperature of reaction and catalyst dosage on the response, where the temperature of reaction shows high effects compared to catalyst dosage.

### 3.3 Desirability Function

The desirability function is a technique used for the determination of optimum settings for independent variables effect on response. The process depends on nominate best levels of independent variables that lead to the most desirable response (optimum) [19]. For this system, the optimum conditions to maximize the sulfur removal efficiency are that  $X_1 = 0.646$ ,  $X_2 = 1$ , and  $X_3 = 1$ , these are corresponding to stirring time = 225 minutes, catalyst dosage = 2.5 grams, and temperature = 60 °C which lead to

Table 4. ANOVA analysis results for RSM for quadratic model.

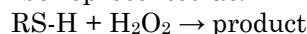
Source	Sum of Squares	df	Mean Square	<i>F</i> -value	<i>P</i> -value	Notes
Model	1082.9	9	120.33	29.11	0.0009	significant
$X_1$ -Time	512	1	512	123.87	0.0001	significant
$X_2$ -Dosage	32	1	32	7.74	0.0388	significant
$X_3$ -Temp.	288	1	288	69.68	0.0004	significant
$X_1X_2$	1	1	1	0.242	0.6436	non-significant
$X_1X_3$	25	1	25	6.05	0.0573	slightly significant
$X_2X_3$	49	1	49	11.85	0.0184	significant
$X_1^2$	77.56	1	77.56	18.77	0.0075	significant
$X_2^2$	31.41	1	31.41	7.6	0.04	significant
$X_3^2$	61.56	1	61.56	14.89	0.0119	significant
$R^2$	0.9813					
Adjusted $R^2$	0.9476					
Predicted $R^2$	0.7087					



maximum sulfur removal efficiency equal to 0.922.

### 3.4 Oxidation Desulfurization Reaction Kinetics

Kinetics for ODS reaction studies under various temperatures against time using optimum catalyst dosage at 2.5 g. The total sulfur content measured with time (1, 2, 3, 4) hours and temperatures (40, 50, 60) °C. Assume oxidation reaction can be represented as:



$$-\frac{d[C_S]}{dt} = k[C_{\text{H}_2\text{O}_2}]^m [C_S]^n \quad (7)$$

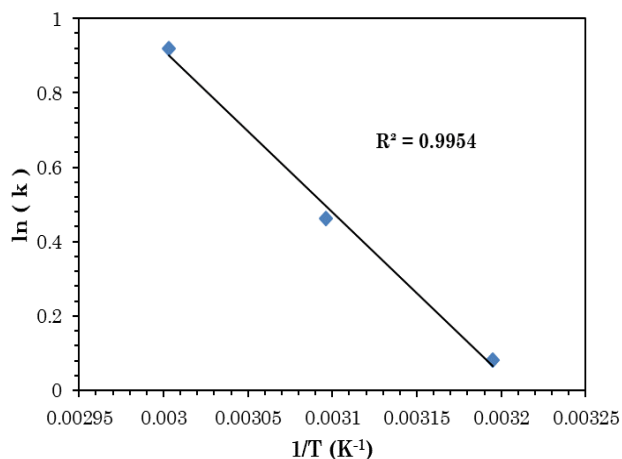
By assume that hydrogen peroxide in excess amount, thus the  $\text{H}_2\text{O}_2$  term dependent can be neglected. Many researchers had been reported that oxidation reaction obeys pseudo first order reaction therefore Equation (7) can be written by assuming  $n = 1$  as:

$$-\frac{d[C_S]}{dt} = k'[C_S] \quad (8)$$

Where  $k'$  is apparent rate constant, integration Equation (8) between below limit:

At  $t = 0 \rightarrow C_s = C_0$  and at  $t = t \rightarrow C_s = C_t$

$$\ln\left(\frac{C_0}{C_t}\right) = k't \quad (9)$$



**Figure 11.** Effect of temperature on reaction rate constant.

**Table 5.** Rate constant values with temperature with correlation factor  $R^2$ .

Temperature (°C)	Rate Constant	$R^2$
40	1.0837	0.9892
50	1.5893	0.9835
60	2.5053	0.9786

Where  $C_s$ ,  $C_0$ , and  $C_t$  are sulfur concentration, initial sulfur concentration and final sulfur concentration [mol/L],  $t$  is time in hour and  $k$  is the reaction rate constant [ $\text{h}^{-1}$ ].

Plotting  $\ln(C_0/C_t)$  against time for various temperatures give straight line represent the rate constant, the straight line with high  $R^2$  which confirms the assumption of kinetics of pseudo first order reaction as shown in Figure 10 and Table 5, as seen in table reaction rate constant is increasing with increased temperature because its strongly temperature dependent [20].

The activation energies ( $E_a$ ) for ODS reaction estimated according to Arrhenius equation [ $k = k_0 \exp(-E_a/RT)$ ] from plot ( $\ln k$ ) vs ( $1/T$ ) as shown in Figure 11, the apparent activation energy value is 36.26 kJ/mol. The estimated activation energy value was close to many estimated values in previous work as shown in Table 6.

## 4. Conclusion

The catalyst characterizations indicate that  $\text{Fe}_2\text{O}_3$  was successfully dispersed on the Graphene surface. The sulfur removal efficiency reached 90% at following operating conditions; 240 min stirring time, 1.5 g catalyst dosage, and 60 °C temperature. The results analyzed with Box–Behnken experimental design by the aim of Design-Expert software shows that among three studied variables (stirring time, catalyst dosage and temperature), stirring time has the highest impact on sulfur removal efficiency via its F-value from ANOVA analysis. The suggested model (second-order polynomial) for experimental results show good convergence with predicated data due to its high  $R^2$  coefficient value (0.9813). The optimization analysis for the statistical model predicted that maximum removal efficiency (0.922) could be estimated by values of three studied process variables; stirring time at 225 min, catalyst dosage at 2.5 grams and temperature at 60 °C. The ODS reaction was obeyed pseud first-order reaction with apparent activation energy value

**Table 6.** Activation energy for dibenzothiophene for various catalyst / $\text{H}_2\text{O}_2$

Catalyst	Activation energy, kJ/mol	Reference
$\text{H}_3\text{PW}_{12}\text{O}_{40}$	45.9	[21]
$\text{H}_3\text{PMO}_{12}\text{O}_{40}$	29.0	[21]
$\text{H}_3\text{SiW}_{12}\text{O}_{40}$	28.3	[21]
HPW/aEVM	30.3	[22]

equal to 36.26 kJ/mol. The sulfur removal efficiency increased with increasing stirring time, catalyst dosage and temperature. The study graded the impact of parameters on the sulfur removal efficiency to be in the order; stirring time, reaction temperature and catalyst dosage. The ODS reaction show activation energy equal to 36.26 kJ/mol. The reaction kinetics has been studied under various range of temperatures and time, while the hydrogen peroxide assumed to be excess and the reaction is first order reaction.

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