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Optimization and Process Modeling of Viscosity of Oil Based Drilling Muds

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Abstract

The viscosity of oil-based drilling mud was optimized and modeled in this study. Imported bentonite and local clay additives, and diesel oil (base fluid) were used to prepare two muds; oil-based mud with bentonite (OBMB) and oil-based mud with clay (OBMC). The local clay was beneficiated with hydrochloric acid (HCl) and then characterized using an x-ray fluorescence (XRF) spectrometer. The result of the characterization revealed that the local clay is more of silica (SiO_2) which is typical of a kaolin. The interactive effects of three operating conditions, temperature, aging time, and bentonite/clay dosage, respectively, on the viscosity of each mud were determined. The Response surface methodology (RSM) of the central composite design tool of Design Expert software (version 12) was employed to optimize the viscosity of each mud. The RSM carried out revealed the interaction between the three operating variables of temperature, time, and dosage of bentonite/clay and their impact on the viscosity of each mud. Optimum viscosity of 19.3 *cP* for OBMB and 25.9 for OBMC were obtained at temperature of 313K, aging time of 30 minutes and bentonite/clay dosage of 9 wt%. Analysis of variants (ANOVA), mathematical modeling, and graphical plots further established the actual interaction between the response-viscosity of each mud and the considered process factors. The generated models revealed linear, interactive, and quadratic equations which adequately described the relationship between the viscosity of each mud and the considered factors of temperature, time, and dosage. The experimental data and the predicted results were compared, and the model predicted values are in good agreement with the experimental results.

Keywords: Bentonite; Local Clay; Optimization; Quadratic Model; Response Surface Methodology; Viscosity; Rheological Properties.

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1. Introduction

The process of designing drilling muds is extremely important and is becoming one of the major focus points [1] in drilling operations. Generally, the main functions of drilling mud include: cooling and lubrication of the drill bit; cleaning the bottom of the hole; removal of drill cuttings to the surface; keeping cuttings in suspension; formation of filter cake; ensuring adequate information from the hole and preventing hole damage to the pay zone; minimizing risk to personnel, the environment, and drilling equipment; transmission of hydraulic horse-power to the bit; stabilizing the wellbore and controlling subsurface pressure [2-4]. In order to obtain superior performance from the drilling mud, optimizing its rheological properties suitable for different types of field/well is very pertinent.

Rheology is an important flow characteristic of muds, and the mud rheology must be controlled at adequate levels so as to provide optimum performance, since it is the basis for all analyses of well bore hydraulics [2]. Rheological

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properties consist of viscosity, gel strength, and yield point. However, viscosity - the internal resistance offered by a fluid to flow, according to Azinta et al. (2021) [4] is considered the most important rheological flow property on account of its ability to hold formation chip at the bottom [5, 6]. Measuring and designing these properties is beneficial in formulating a good mud that can remove cuttings, hold cuttings and weight materials in suspension when not circulating, release cuttings at the surface and reduce to a minimum any adverse effect on the well bore [7] that could result in financial loss and, in extreme cases, abandonment of the well. In order to fulfil the requirements of different drilling wells, the rheological properties of drilling muds are enhanced using various additives for the mud formation. Additives commonly used in drilling mud formulations are; viscosifiers, viscosity reducers, weighting materials, fluid-loss reducers, lost circulation materials, corrosion control chemicals, and pH control additives [3].

It is essential for a mud engineer to understand the changes in mud rheology particularly viscosity brought about by varying subsurface conditions especially in oil wells [7]. In order to allot the most suitable drilling mud, a good understanding of the variation in mud rheology with temperature, mixing time and dosage of viscosity control agents (clay materials – clay/bentonite) is necessary. A model will be required to further understand these variations, more specifically in regards to factors such as viscosity.

Depending on the base materials/fluids used, drilling muds are classified into three major types; water based mud (WBM), oil based mud (OBM), and synthetic based mud (SBM). Compared to other types of drilling muds, OBM has the prominent advantages of higher penetration rate, thermal stability in deep high-temperature wells, increased lubricity in deviated offshore wells, and hole stability in thick, water-sensitive shales [7, 8]. Well friction is lowered with oil-based drilling fluids. They are also often used in long-reach wells where friction is a paramount factor [1]. Furthermore, oil based muds offer excellent corrosion protection and could be stored for longer periods of time [5]. Considering the practical applicability of this study, an important area of application is in designing a suitable drilling mud for drilling geothermal wells, in addition to understanding the nature of wells since well situations may vary on account of geographical location [7, 9-12].

In this work, the viscosity of formulated oil based mud with bentonite (OBMB) and oil based mud with clay (OBMC) respectively, were optimized using response surface methodology and modelled, thereby revealing the effects of three process factors (aging time of mixture, temperature and bentonite/clay dosage) on the viscosity of each mud. Other rheological properties (such as gel strength, yield point, mud weight, and pH) of each of the formulated muds were determined as viscosity accompanying/allied rheological properties. Several studies have been carried out on the production of drilling mud and its additives, and the effects of aging time and temperature on the rheological and allied properties of drilling muds [13-16]. However, there is very little experimental data available that pertains to the optimization of viscosity of drilling muds and to the understanding of the interaction between the flow behavior of OBMB and OBMC (with particular emphasis on local clay from Awgu region in Enugu State, Nigeria), and the operating process factors of temperature, time and dosage. From the review of the previous studies, there is need to carry out the optimization study and process modeling of viscosity of oil based muds.

2. Materials and Method

2.1. Equipment and Raw Materials

The equipment used in this work include; graduated measuring cylinder, beakers, electronic weighing balance, mixer, viscometer, drilling mud balance, water bath, pH meter, and stop watch. The raw materials used in the formulation of the oil based drilling fluids using bentonite and Awgu clay are presented in Table 1.

Table 1. The raw materials used for the formulation of OBMB and OBMC

Properties	Functions	Quantity
Diesel oil	Base fluid	240 ml
Bentonite/Clay	Viscosity and filtration control	9.0 g
Xanthum cum biopolymer (XCD)	Viscosity and fluid-loss control in lowsolid muds	0.6 g
High viscosity polyanionic cellulose(PAC-R)	Fluid loss control and viscosifier	0.5 g
Modified natural polyanionic cellulose(PAC-L)	Fluid loss control and viscosifier	0.3 g
Potassium hydroxide (KOH)	Potassium source for inhibitive purpose	0.2 g
Sodium carbonate (Na_2CO_3)	Calcium precipitant	6.0 g
Barite	Weighing agent	13.0 g

2.2. Experimental Procedure

The local clay obtained from Awgu region in Enugu State, Nigeria (Figure 1) was beneficiated according to the method used by Omotioma et al. (2015) and Azinta et al. (2021) [3, 4]. The various quantities of the raw materials were measured using a graduated cylinder and electronic weighing balance. The raw materials were then poured, one after the other, with an interval of 5 minutes into the steel cup of the single spindle mixer in a descending order as arranged in Table 1. As each material is being put into the mixer, the mixer is powered to cause the spindle to rotate and mix the contents inside the steel cup being held at a fixed position. As the materials have been completely applied into the mixer steel cup, it was allowed to age for 30 minutes, under stirring condition, for a total uniformity of the materials to give finely formulated oil based drilling mud whose colour appears brownish. The production methods and determination of the rheological and allied properties of the drilling muds were carried out based on the American Petroleum Institute (API) drilling mud production standards [3]. The mixing method used by Kinate and Dune (2016) [17] was adopted. Drilling mud balance was used to measure the density of the mud. Viscometer was used for the measurement of rheological properties of the formulated drilling mud. The rheological readings, API Testing, 600 RPM (revolution per minutes), 300 RPM, 6 RPM and 3 RPM, were recorded. Also, 10 seconds, 10 minutes and 30 minutes gel strength values were recorded. The plastic viscosity and yield point values were appropriately evaluated. The pH meter was used to measure the pH of the formulated drilling mud. This procedure is carried out in triplicate, and average value for each parameter was obtained. OBMB was formulated first, then followed by OBMC.

Figure 1. Map of Awgu in Enugu State showing location of study area

2.3. Optimization Study of Viscosity

The optimization of the viscosity was done using central composite design of response surface methodology. Design Expert software (version 12 trial version) was used in this study to design the experiments and to analyze significance of the model and determination of the optimum values of viscosity of each of the muds. The experimental design employed in this work was a one-level three factor fractional factorial design, involving 20 experiments. Temperature, time of mixing and dosage of bentonite/clay were selected as independent factors for the optimization study. The response chosen was one of the most important mud rheological property – viscosity of the formulated OBMB and OBMC.

3. Results And Discussion

3.1. Characterization of Beneficiated Clay

The characterization results of the beneficiated clay sample using X-Ray fluorescence, Philips PW 2400 XRF spectrometer are shown in Table 2. It shows that the beneficiated clay sample is more of silica (SiO_2) which is typical of a kaolinitic clay [4].

Table 2. X-ray fluorescence spectrometer of the beneficiated local clay

Oxides	Beneficiated clay (%)
Al_2O_3	14.45
SiO_2	68.54
K_2O	0.05
TiO_2	0.69
MnO	0.08
Fe_2O_3	13.36
SrO	0.01
Nb_2O_5	0.01
MoO_3	0.06
Ag_2O	0.01
CdO	0.08
HfO_2	<0.01
PbO	<0.01
TaO	<0.01
Total	**97.34**

3.2. Rheological Properties

The results of the rheological properties of the formulated oil based mud with bentonite (OBMB) and oil based mud with local clay (OBMC) at the optimum operating conditions of 9wt% bentonite/clay dosage, 30 minutes aging time and 313K temperature, including their dial readings are presented in Table 3. The table shows the values of other allied rheological properties of the formulated muds.

Table 3. Results obtained from the experiment at optimum process conditions

Properties	OBMB	OBMC
Mud weight (lb./gal)	9.21	9.24
pH	9.70	9.80
600rpm	47.8	60.2
300rpm	28.1	33.7
Plastic viscosity	19.7	26.5
Apparent viscosity	23.9	30.1
Yield point	8.4	7.1
Gel Strength (10 sec), lb./100ft^2	3.2	3.9
Gel Strength (10 min), lb./100ft^2	5.3	6.0
Gel Strength (30 min), lb./100ft^2	6.4	6.9

RPM (Revolution per minute)

The Plastic viscosity, yield point and apparent viscosity of each mud were calculated using Equations 1, 2, and 3 respectively [3, 4]:

$$Plastic\ Viscosity\ (PV), cP = 600RPM\ reading - 300RPM\ reading \tag{1}$$

$$Yield\ Point\ (YP), lb/100ft^2 = 300RPM\ reading - PV \tag{2}$$

$$Apparent\ Viscosity\ (AV), cP = 600RPM\ reading/2 \tag{3}$$

3.3. Optimization of Viscosity of OBMB and OBMC

Optimization Results of Viscosity of OBMB and OBMC

The response surface methodology results of viscosity of OBMB and OBMC are presented in Tables 4 and 5 respectively. The tables revealed interactive effects of dosage of bentonite/clay, temperature and time on viscosity of the muds. Values of the viscosity of each mud were at optimum in the mid-points of the considered factors. This is an indication of parabolic relationship between the viscosity response and the process factors. Further analyses are required to establish the actual relationship between the response (viscosity) and factors of dosage of bentonite/clay, temperature and time. Such analyses include analysis of variance (ANOVA), mathematical modeling and graphical plots.

Table 4. RSM results of viscosity of OBMB

Std	Run	Factor 1, A: Dosage of Bentonite, *wt%*	Factor 2, B: Temperature *K*	Factor 3, C: Time Minutes	Response Viscosity ***cP***
17	1	9	313	30	19.7
9	2	3	313	30	18.4
16	3	9	313	30	19.7
13	4	9	313	10	16.2
6	5	15	303	50	16.3
14	6	9	313	50	17.6
19	7	9	313	30	19.7
1	8	3	303	10	14.6
3	9	3	323	10	14.5
12	10	9	323	30	15.6
7	11	3	323	50	16.5
10	12	15	313	30	15.4
18	13	9	313	30	19.7
15	14	9	313	30	19.7
8	15	15	323	50	6.5
5	16	3	303	50	17.2
4	17	15	323	10	7.4
11	18	9	303	30	17.5
20	19	9	313	30	19.7
2	20	15	303	10	15.3

Table 5. RSM results of viscosity of OBMC

Std	Run	Factor 1, A: Dosage of Clay, wt%	Factor 2, B: Temperature K	Factor 3, C: Time Minutes	Response Viscosity ***cP***
17	1	9	313	30	26.5
9	2	3	313	30	23.2
16	3	9	313	30	26.5
13	4	9	313	10	22.4
6	5	15	303	50	19.9
14	6	9	313	50	25
19	7	9	313	30	26.5
1	8	3	303	10	18.8
3	9	3	323	10	14
12	10	9	323	30	18.1
7	11	3	323	50	19.3
10	12	15	313	30	20.1
18	13	9	313	30	26.5
15	14	9	313	30	26.5
8	15	15	323	50	9.7
5	16	3	303	50	21.4
4	17	15	323	10	8.7
11	18	9	303	30	22.2
20	19	9	313	30	26.5
2	20	15	303	10	19.4

Analysis of Variance of Viscosity of OBMB and OBMC

The Analysis of variance (ANOVA) of viscosity of OBMB and OBMC are shown in Tables 6 and 7 respectively. The ANOVA was applied for estimating the significance of the model at 5% significance level. A model is considered significant if the *p-value* (significant probability value) is less than 0.05 and highly significant if the *p-value* is < 0.0001 [18, 19]. From the *p-values* presented in Tables 6 and 7, it can be deduced that model terms A, B, and AB for OBMB, and B and B^2 for OBMC are highly significant terms. Also, all the linear terms A, B, and C, interactive term AB, and the quadratic terms A^2, B^2 and C^2 are significant model terms for OBMB and OBMC (except C^2 term for OBMC). Based on this, the insignificant terms AC and BC for OBMB, and AC, BC and C^2 for OBMC of the models were removed and the models reduced to Equations 4 and 6 respectively in previous Section. The Predicted R^2 of 0.8248 and 0.8746 for OBMB and OBMC respectively are in reasonable agreement with the Adjusted R^2 of 0.9504 and 0.9630 for OBMB and OBMC respectively, since the differences are less than 0.15 in each case. Adequate Precision measures the signal to noise ratio. A ratio greater than 4 is desirable for both models. The ratio of 21.475 and 23.639 for OBMB and OBMC respectively, indicate adequate signals. These models can be used to navigate the design space [20].

Table 6. ANOVA results of viscosity of OBMB

Source	Sum of Squares	D$_f$	Mean Square	*F-value*	*p-value*	
Model	254.54	9	28.28	41.44	< 0.0001	Significant
A-Dosage of bentonite	41.21	1	41.21	60.37	< 0.0001	
B-Temperature	41.62	1	41.62	60.97	< 0.0001	
C-Time	3.72	1	3.72	5.45	0.0417	
AB	35.70	1	35.70	52.31	< 0.0001	
AC	2.53	1	2.53	3.71	0.0830	
BC	0.7813	1	0.7813	1.14	0.3098	
A^2	9.50	1	9.50	13.93	0.0039	
B^2	13.42	1	13.42	19.66	0.0013	
C^2	9.50	1	9.50	13.93	0.0039	
Residual	6.83	10	0.6826			
Lack of Fit	6.83	5	1.37			
Pure Error	0.0000	5	0.0000			
Cor Total	261.37	19	R^2		0.9739	
Std. Dev.	0.8262		Adjusted R^2		0.9504	
Mean	16.36		Predicted R^2		0.8248	
C.V. %	5.05		Adeq Precision		21.4754	

Table 7. ANOVA results of viscosity of OBMC

Source	Sum of Squares	df	Mean Square	*F-value*	*p-value*	
Model	543.72	9	60.41	55.91	< 0.0001	Significant
A-Dosage of clay	35.72	1	35.72	33.06	0.0002	
B-Temperature	101.76	1	101.76	94.18	< 0.0001	
C-Time	14.40	1	14.40	13.33	0.0045	
AB	24.50	1	24.50	22.67	0.0008	
AC	5.12	1	5.12	4.74	0.0545	
BC	1.28	1	1.28	1.18	0.3020	
A^2	32.39	1	32.39	29.97	0.0003	
B^2	66.89	1	66.89	61.90	< 0.0001	
C^2	5.25	1	5.25	4.86	0.0520	
Residual	10.81	10	1.08			
Lack of Fit	10.81	5	2.16			
Pure Error	0.0000	5	0.0000			
Cor Total	554.53	19		R^2		0.9805
Std. Dev.	1.04			Adjusted R^2		0.9630
Mean	21.06			Predicted R^2		0.8746
C.V. %	4.94			Adeq Precision		23.6394

Mathematical Model of Viscosity of OBMB and OBMC

The mathematical model of viscosity of OBMB and OBMC for significant (VBS and VCS) model terms and general (VBG and VCG) model terms are expressed in Equations 4 and 6, and in Equations 5 and 7. Equations 4 and 6 contain only significant model terms for OBMB and OBMC respectively, while Equations 5 and 7 contain general model terms for OBMB and OBMC respectively. These equations revealed that the highest power of the factors is 2 which is typical of a quadratic equation.

$$\mathrm{VBS} = +19.32 - 2.03\mathrm{A} - 2.04\mathrm{B} + 0.6100\mathrm{C} - 2.11\mathrm{AB} - 1.86\mathrm{A}^2 - 2.21\mathrm{B}^2 - 1.86\mathrm{C}^2 \tag{4}$$

$$\mathrm{VBG} = +19.32 - 2.03\mathrm{A} - 2.04\mathrm{B} + 0.6100\mathrm{C} - 2.11\mathrm{AB} - 0.5625\mathrm{AC} - 0.3125\mathrm{BC} - 1.86\mathrm{A}^2 - 2.21\mathrm{B}^2 - 1.86\mathrm{C}^2 \tag{5}$$

$$\mathrm{VCS} = +25.93 - 1.89\mathrm{A} - 3.19\mathrm{B} + 1.20\mathrm{C} - 1.75\mathrm{AB} - 3.43\mathrm{A}^2 - 4.93\mathrm{B}^2 \tag{6}$$

$$\mathrm{VCG} = +25.93 - 1.89\mathrm{A} - 3.19\mathrm{B} + 1.20\mathrm{C} - 1.75\mathrm{AB} - 0.8000\mathrm{AC} + 0.4000\mathrm{BC} - 3.43\mathrm{A}^2 - 4.93\mathrm{B}^2 - 1.38\mathrm{C}^2 \tag{7}$$

Graphical Analysis of Viscosity of OBMB and OBMC

The predicted versus actual viscosity of OBMB and OBMC are shown in Figures 2 and 3 respectively. The figures revealed linear graphs where the points clustered along the lines of best fits. This is an indication that the generated models can be used to adequately predict viscosity of OBMB and OBMC.

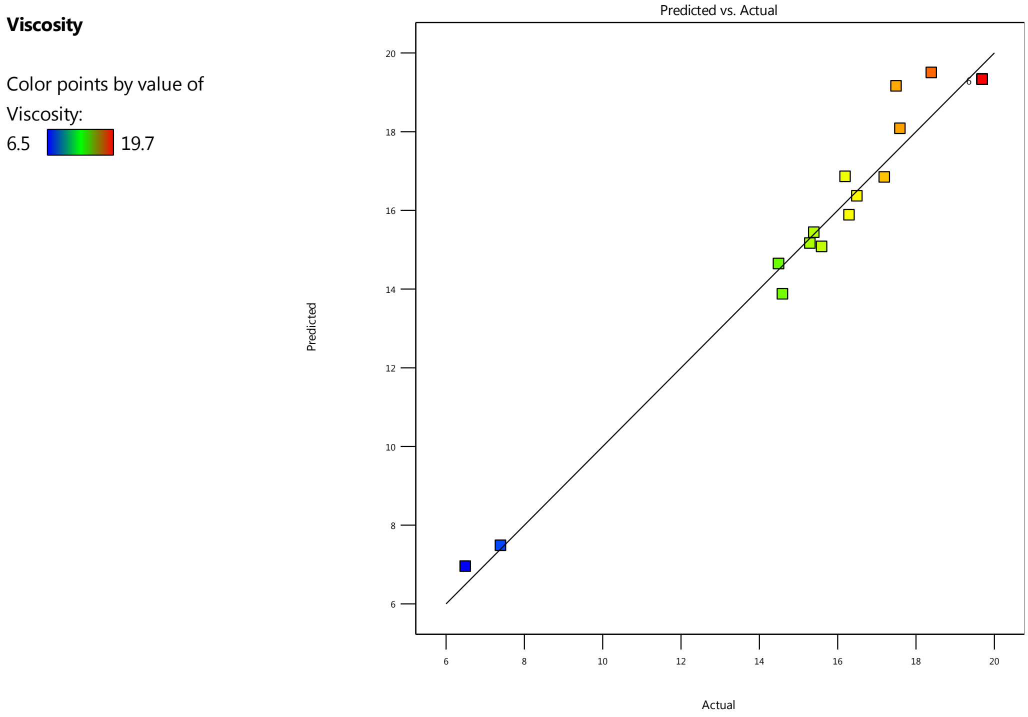

Figure 2. Predicted versus actual viscosity of OBMB

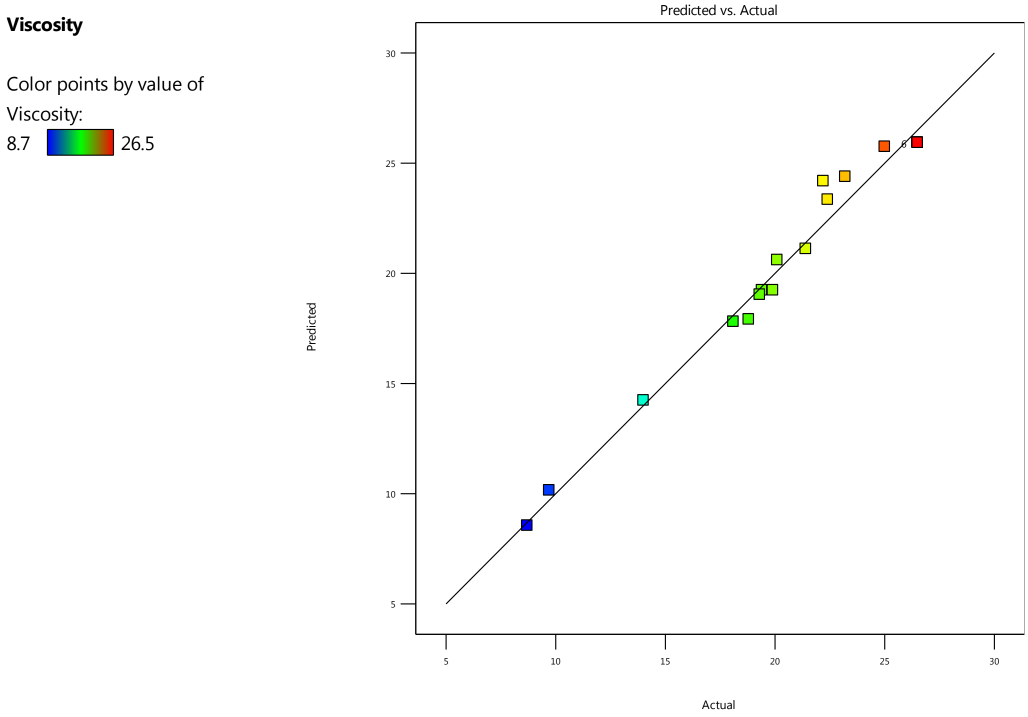

Figure 3. Predicted versus actual viscosity of OBMC

Surface Plots for Viscosity of OBMB and OBMC

The 3D response surface was generated to estimate the effect of the combinations of the independent variables on the viscosity of OBMB and OBMC. The plots are shown in Figures 4 to 9. Figure 4 shows the dependency of viscosity of OBMB on the interaction of temperature and dosage of bentonite. As can be seen from Figure 4, viscosity of OBMB increases as both temperature and dosage of bentonite increase. It is a scientific fact that viscosity of fluids decreases with increase in temperature but increase with increase in dosage of clay materials [15, 21]. This shows that the effect of increase in temperature balances the effect of increase in dosage of bentonite on the viscosity of OBMB.

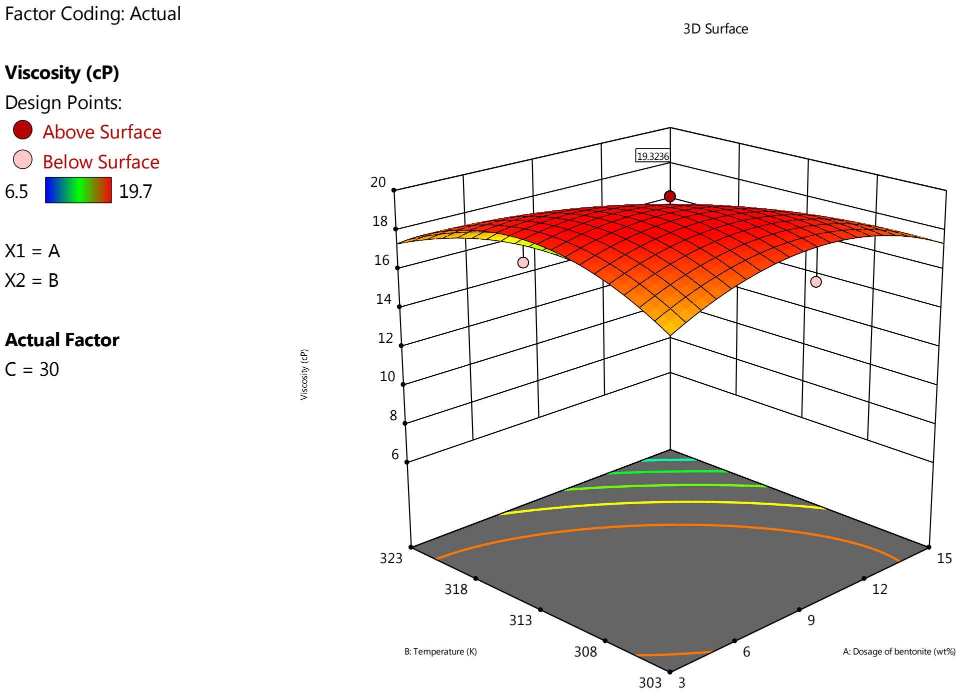

Figure 4. Effect of temperature and dosage of bentonite on viscosity of OBMB

Figure 5 shows the dependency of viscosity of OBMB on the interactive effect of time and dosage of bentonite. This shows that the viscosity of OBMB increases as both time and dosage of bentonite increase. However, the increase in viscosity is sharper with increase in time (at mid-point of 30 mins) than with increase in dosage of bentonite. This might be explained from the fact that the degree of dispersion and flocculation increased when the mud was aged statically [15].

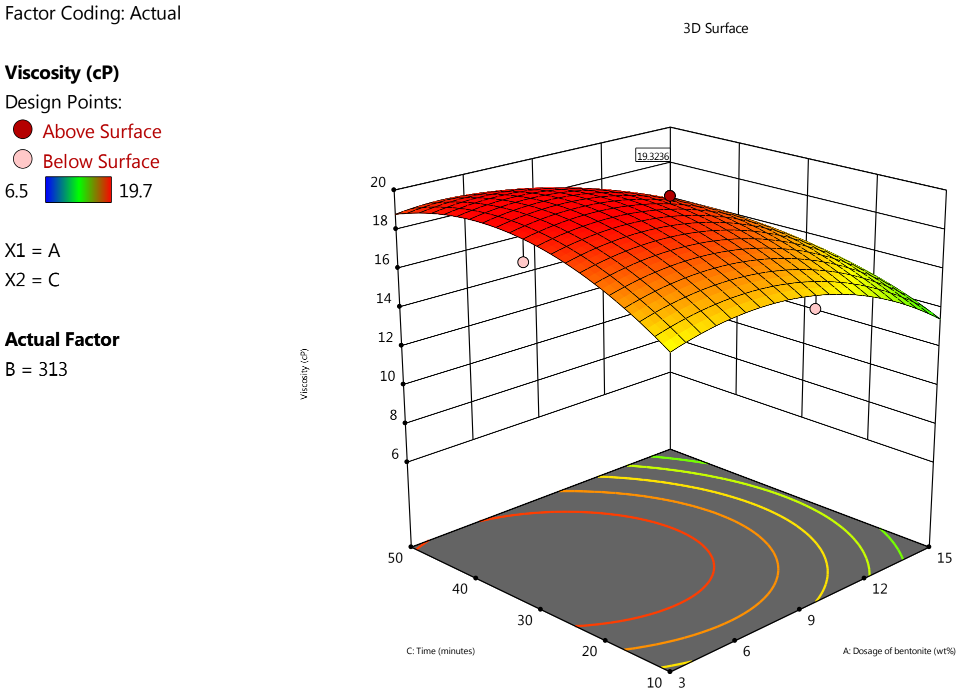

Figure 5. Effect of time and dosage of bentonite on viscosity of OBMB

Figure 6 shows the dependency of viscosity of OBMB on the interaction of temperature and time. The viscosity of OBMB increases as both temperature and time increase, but the increase of viscosity with time is more rapid linearly than with temperature.

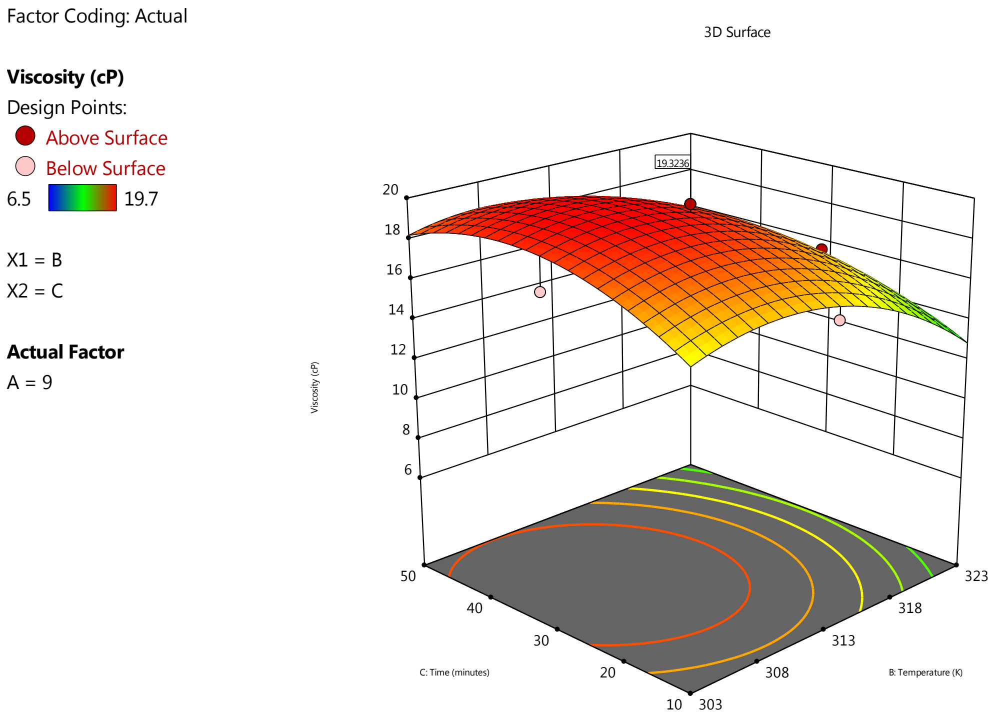

Figure 6. Effect of temperature and time on viscosity of OBMB

Figure 7 shows the dependency of viscosity of OBMC on the interaction of temperature and dosage of clay. As can be seen from the Figure 7, viscosity of OBMC increases as both temperature and dosage of clay increase. This is in good agreement with the findings by Apugo-Nwosu (2011) [15].

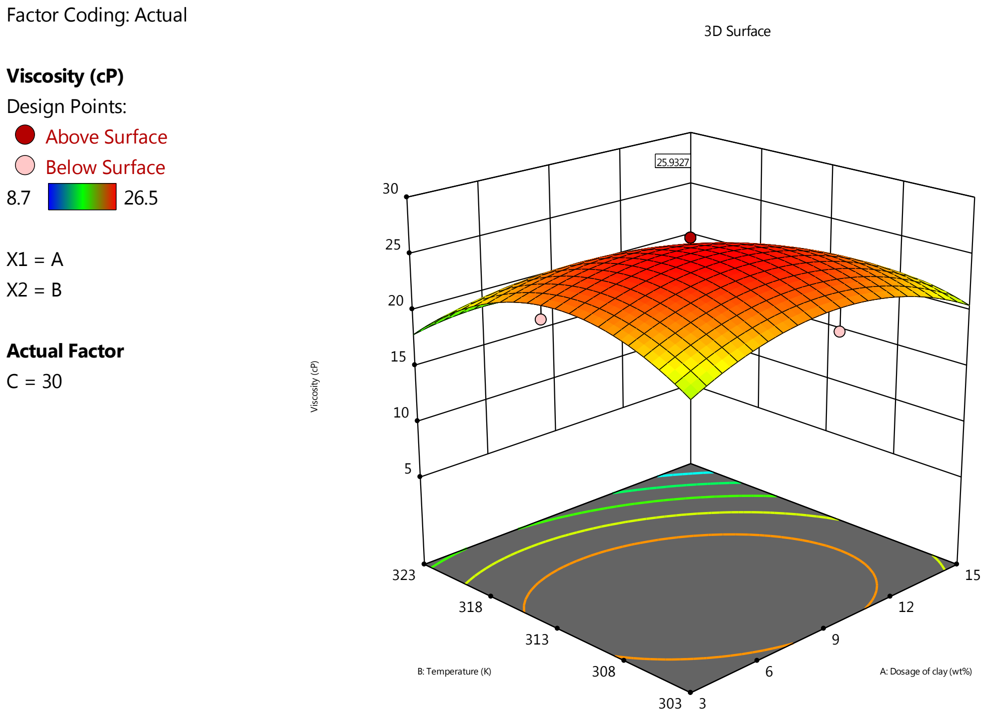

Figure 7. Effect of temperature and dosage of clay on viscosity of OBMC

Figure 8 shows the dependency of viscosity of OBMC on the interaction of time and dosage of clay. The viscosity of OBMC increases as both time and dosage of clay increase. But, the increase in viscosity of OBMC with time is almost parallel to the time axis. This shows a minor effect of time on viscosity.

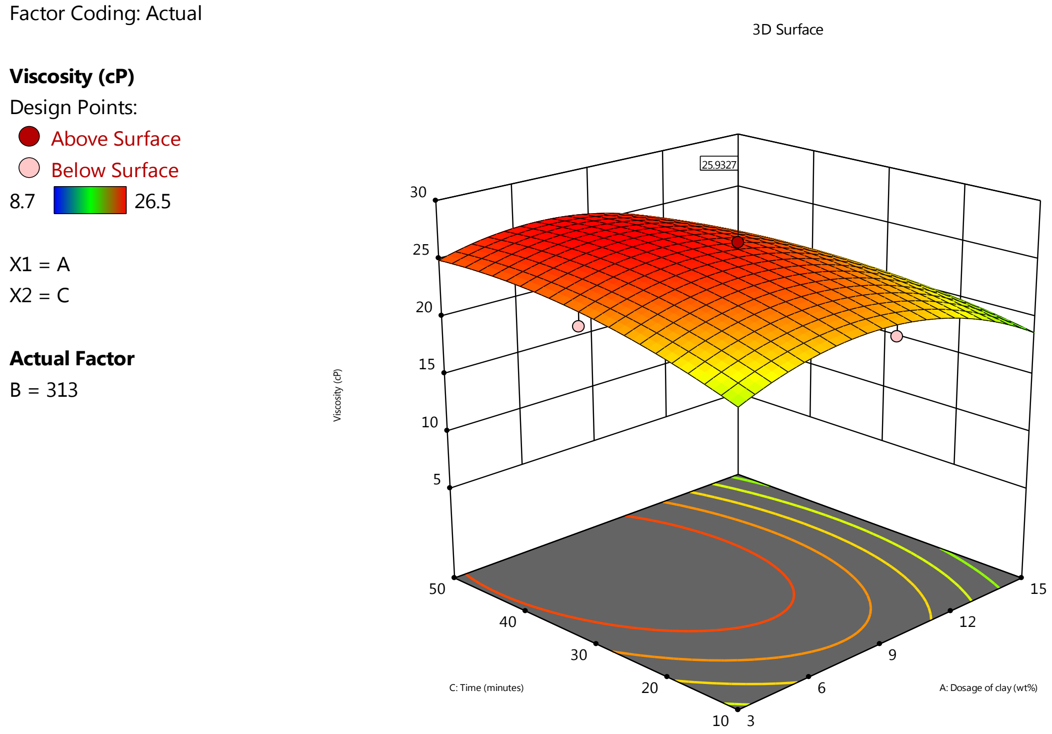

Figure 8. Effect of time and dosage of clay on viscosity of OBMC

Figure 9 shows the dependency of viscosity of OBMC on the interaction of time and temperature. The viscosity of OBMC increases as both time and temperature increase. However, the viscosity of OBMC increases linearly with increase in time, and radially with increase in temperature. This shows that increasing time of mixing is not very necessary as viscosity increases.

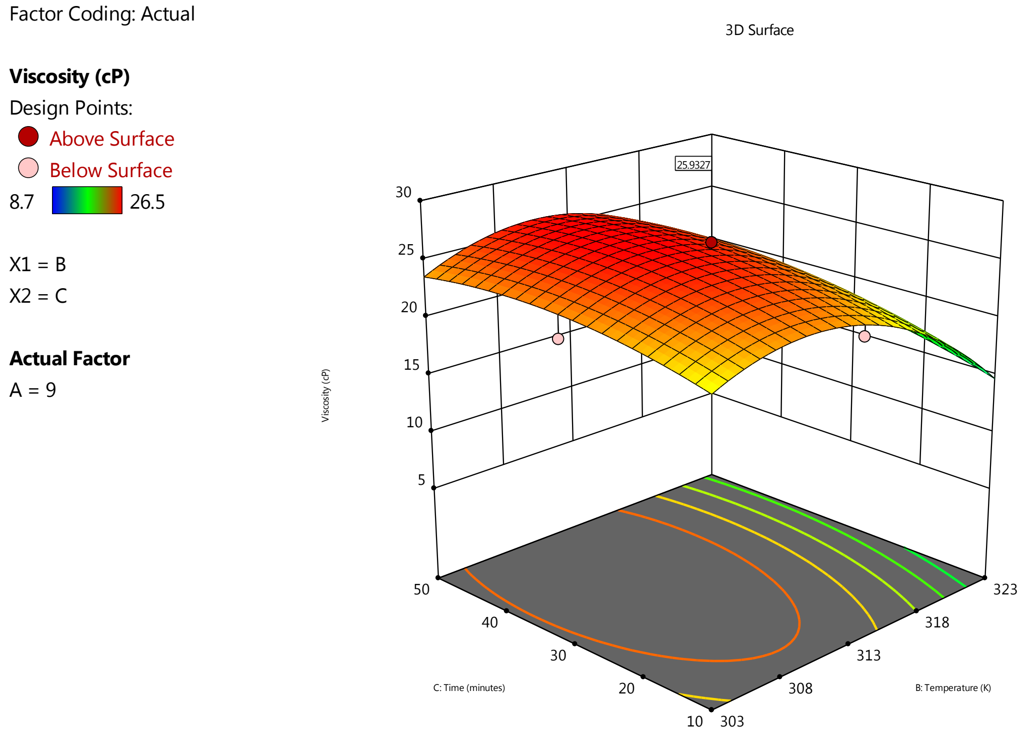

Figure 9. Effect of time and temperature on viscosity of OBMC

3.3.2. Optimum Parameters

The optimum parameters; optimum dosage, optimum temperature, optimum time and optimum response (viscosity) of OBMB and OBMC respectively are shown in Table 8. It revealed the values of the optimum viscosity of each of the drilling muds (OBMB and OBMC) at the mid-point/optimum operating conditions.

Table 8. Optimum Parameters

Sample	Optimum Dosage (wt, %)	Optimum Temperature (K)	Optimum Time (min)	Optimum Viscosity (cP)
OBMB	9	313	30	19.3
OBMC	9	313	30	25.9

3.3.3. Validation of Results

The validation of results for optimum dosage, optimum temperature, optimum time, and experimental and predicted viscosities for OBMB and OBMC, respectively, together with the percentage deviations, are shown in Table 9. The experimental viscosity and the predicted viscosity are in good agreement since the percentage deviation for each mud is less than 3% [18]. This indicates that the models can adequately predict the viscosity of OBMB and OBMC [19]. Furthermore, the optimum viscosity responses of each of the muds in Table 8 are approximate values of the average experimental and predicted viscosity values of each mud in Table 9.

Table 9. Validation of the Results

Sample	Optimum Dosage (wt, %)	Optimum Temperature (K)	Optimum Time (min)	Experimental Viscosity (cP)	Predicted Viscosity (cP)	Predicted Viscosity (cP)
OBMB	9	313	30	19.2	19.7	2.6
OBMC	9	313	30	25.8	26.5	2.7

4. Conclusions

At the end of this optimization study and modeling of the process variables of the viscosity of oil based muds, the following conclusions were arrived at:

- The viscosity model of each of the formulated muds depends on temperature, time, and dosage of bentonite/clay;
- The experimental and predicted viscosity responses of each of the formulated muds are in good agreement;
- The optimum viscosity responses of each of the muds are approximate values of the average experimental and predicted viscosity values of each mud;
- The generated viscosity model of each of the formulated muds revealed a linear, interactive, and quadratic relationship with the process factors of dosage, temperature, and time;
- The optimum viscosity of each of the formulated muds was obtained at the mid-points of the considered process factors of dosage, temperature, and time;
- Dosage of bentonite (A), temperature (B), and the interaction of dosage of bentonite and temperature (AB) are highly significant model terms for optimizing the viscosity of oil based mud with bentonite (OBMB);
- Temperature (B) and the quadratic term of temperature (B^2) are highly significant model terms for optimizing the viscosity of oil based mud with clay (OBMC);
- The linear model term, time (C), has very little effect on both the viscosity of OBMB and OBMC, but particularly, OBMC.

5. Declarations

5.1. Author Contributions

Conceptualization, A.C.O. and G.O.M.; methodology, A.C.O.; software, A.C.O.; validation, A.C.O., G.O.M. and M.I.O.; formal analysis, A.C.O.; investigation, A.C.O.; resources, A.C.O.; data curation, A.C.O.; writing—original draft preparation, A.C.O.; writing—review and editing, A.C.O.; visualization, A.C.O.; supervision, G.O.M.; project administration, A.C.O. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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5.4. Declaration of Competing Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

6. References

[1] Zhuang, G., Zhang, Z., Fu, M., Ye, X., & Liao, L. (2015). Comparative study on the use of cationic-nonionic-organo-montmorillonite in oil-based drilling fluids. Applied Clay Science, 116–117, 257–262. doi:10.1016/j.clay.2015.04.004.

[2] Charles, O., & Adetokunbo, F. (2017). Comparative Study of the Rheological Properties of Local Clay (Afuze) as a Possible Replacement for Imported Bentonite in Drilling Fluids Formulation. International Journal of Scientific & Engineering Research, 8(11), 249–255.

[3] Omotioma, M., Ejikeme, P. C. N., & Ume, J. I. (2015). Improving the rheological properties of water based mud with the addition of cassava starch. IOSR Journal of Applied Chemistry, 8(8), 70–73.

[4] Azinta, C. O., Mbah, G. O., & Omotioma, M. (2021). Analysis of Effects of Foreign Clay and Local Clay Additives on Viscosity of Water Based Drilling Mud. Journal of Engineering Research and Reports, 21(4), 60–67. doi:10.9734/jerr/2021/v21i417459.

[5] Kassab, S. Z., Ismail, A. S., & Elessawi, M. M. (2011). Drilling fluid rheology and hydraulics for oil fields. European Journal of Scientific Research, 57(1), 68–86.

[6] Yunita, P., Irawan, S., & Kania, D. (2016). Optimization of Water-based Drilling Fluid Using Non-ionic and Anionic Surfactant Additives. Procedia Engineering, 148, 1184–1190. doi:10.1016/j.proeng.2016.06.628.

[7] Amani, M. (2012). The Rheological Properties of Oil-Based Mud under High Pressure and High Temperature Conditions. Advances in Petroleum Exploration and Development, 3(2), 21–30. doi:10.3968/j.aped.1925543820120302.359.

[8] Gusler, W., Pless, M., Maxey, J., Gorver, P. E., Perez, J., Moon, J., & Boaz, T. (2007). A new extreme-HP/HT viscometer for new drilling-fluid challenges. In SPE Drilling and Completion (Vol. 22, Issue 2, pp. 81–89). doi:10.2118/99009-pa.

[9] Murtaza, M., Alarifi, S. A., Kamal, M. S., Onaizi, S. A., Al-Ajmi, M., & Mahmoud, M. (2021). Experimental Investigation of the Rheological Behavior of an Oil-Based Drilling Fluid with Rheology Modifier and Oil Wetter Additives. Molecules, 26(16), 4877. doi:10.3390/molecules26164877.

[10] Huang, Y., Zheng, W., Zhang, D., & Xi, Y. (2019). A modified Herschel–Bulkley model for rheological properties with temperature response characteristics of poly-sulfonated drilling fluid. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 42(12), 1464–1475. doi:10.1080/15567036.2019.1604861.

[11] Keshavarz Moraveji, M., Ghaffarkhah, A., Agin, F., Talebkeikhah, M., … Arjmand, M. (2020). Application of amorphous silica nanoparticles in improving the rheological properties, filtration and shale stability of glycol-based drilling fluids. International Communications in Heat and Mass Transfer, 115, 104625. doi:10.1016/j.icheatmasstransfer.2020.104625.

[12] Martín-Alfonso, M. J., Mejía, A., Martínez-Boza, F. J., & Martín-Alfonso, J. E. (2021). Rheological characterization of sepiolite-vegetable oil suspensions at high pressures. Applied Clay Science, 212, 106220. doi:10.1016/j.clay.2021.106220.

[13] Makinde, F. A., Adejumo, A. D., Ako, C. T., & Efeovbokhan, V. E. (2011). Modelling the effects of temperature and aging time on the rheological properties of drilling fluids. Petroleum and Coal, 53(3), 167–182.

[14] Abduo, M. I., Dahab, A. S., Abuseda, H., AbdulAziz, A. M., & Elhossieny, M. S. (2016). Comparative study of using Water-Based mud containing Multiwall Carbon Nanotubes versus Oil-Based mud in HPHT fields. Egyptian Journal of Petroleum, 25(4), 459–464. doi:10.1016/j.ejpe.2015.10.008.

[15] Apugo-Nwosu, T. (2011). Studies on the Suitability of Ubakala Bentonitic Clay for Oil Well Drilling Mud Formulation. British Journal of Applied Science & Technology, 1(4), 152–171. doi:10.9734/bjast/2011/407.

[16] Allawi, R. H., Najem, M. A., Sagger, M. A., & Abd, S. M. (2019). Effect of Temperature on Drilling Mud. Journal of Physics: Conference Series, 1279(1), 012054. doi:10.1088/1742-6596/1279/1/012054.

[17] Kinate, B. B., & Dune, K. K. (2016). Comparative study of the rheological properties of Niger Delta crude oil Journal of Scientific and Engineering Research, 3(6), 323.

[18] Samuel Ogbonnaya, E., Gordian Onyebuchukwu, M., & Ebere Rita, M.-I. (2018). Optimization And Process Modeling Of The Extraction Of Alumina From Aku Clay By Hydrochloric Acid Leaching. American Journal of Engineering Research (AJER, 7(7), 158–169.

[19] Oyegoke, T. (2013). Optimization of Rheological and Filtration Properties of Nigeria Clay using Factorial Design. International Journal of Innovative Scientific & Engineering Technologies Research, 1(1), 25–36.

[20] Azinta, C. O. (2021). Comparative analysis of effects of bentonite and Awgu clay additives on the rheological properties of oil and water based drilling muds. Master’s Thesis, Chemical Engineering Department, Enugu State University of Science and Technology, Enugu, Nigeria.

[21] Li, M.-C., Wu, Q., Lei, T., Mei, C., Xu, X., Lee, S., & Gwon, J. (2020). Thermothickening Drilling Fluids Containing Bentonite and Dual-Functionalized Cellulose Nanocrystals. Energy & Fuels, 34(7), 8206–8215. doi:10.1021/acs.energyfuels.0c01192.