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Petroleum & Petrochemical Engineering Journal
ISSN: 2578-4846

Effect of Inhibitors with Aromatic Solvents towards the Flow Properties of Crude Oil

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Research article

Volume 3 Issue 2

Received Date: June 14, 2019

Published Date: June 26, 2019

DOI: 10.23880/ppej-16000193

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Abstract

Petroleum industry which is well known for its growth facing a major issue in transporting crude oil in the pipeline. The major issue which disrupts the flow in the pipeline is due to the fluctuation of the temperature gradient. The temperature in the pipeline normally falls below the room temperature and even reaches negative Celsius as the crude oil drilled off from oil rig. Certain components which appear in crude oil will tend to solidify or crystalize when the temperature in the pipelines decrease. Wax and asphaltene particle affects the flow properties as it will deposit or precipitate along the wall of pipelines which will block the flow by reducing the diameter of the pipelines. Viscosity will tend to increase when the wax and asphaltene particle precipitate in the crude oil. Hence, chemical injection method is implemented whereby inhibitor composed of three components are mixed together crude oil to measure the reduction of viscosity. The main objective of this research paper is to formulate the optimum ratio of components composed of Poly Octadecyl methacrylate (PODMA), Toluene (TOL), Methylcyclohexane (MCH) to form an inhibitor. The viscosities of the crude oil is recorded at the targeted temperature range which compliance with the Wax Appearance Temperature (WAT) of the crude oil. Response Surface Methodology (RSM) is used before and after conducting the experiments in order to build the model and to get the optimized ratio of the components for the reduction of viscosity. Aspen HYSYS is also used to validate the results obtained from the experimental procedure. The final results show that the optimum ratio for the reduction of viscosity is 30% PODMA, 40% MCH and finally 50% TOL.

Keywords: Crude oil; Temperature gradient; Viscosity; Wax inhibitor; Response surface methodology (RSM)

Introduction

Crude oil is unrefined petroleum which plays a vital role in the industry as it can be refined into many valuable products. The demand for the crude oil kept on increasing as it plays a major role in most of leading industries [1]. It is normally the accumulation of hydrocarbon consisting of waxes, asphaltenes, resins, aromatics and naphthenic [2]. Parameters such as viscosity, API gravity and Saturate, Aromatic, Resin and Asphaltene (SARA) analysis helps in

analyzing the crude oils and their derivatives [3]. The findings which indicate higher API shows that the crude oil contains greater properties of gasoline while the lower API indicates the abundant amount of aromatics found in crude oil [4].

Wax appearance temperature (WAT) is the point whereby the wax particle starts to precipitate. Determination of WAT can be done through several tests which include cross-polarized microscopy, cold finger, light transmittance, and ultrasonic methods. In a study conducted by [5], WAT of crude oil samples is measured by the DSC method. In addition, Alghanduri [6] measured WAT using Mettler DSC822. Formation of wax is due to the higher molecular of crude oil which solidify when the temperature of pipelines fall. When the temperature of the pipelines falls below WAT the wax will crystallize [7]. Wax precipitation also is known as reversible as increasing the temperature would melt back the wax formed [8]. The formation of wax would also lead to the formation of asphaltene in pipelines.

Asphaltene is the component in oil which has the highest number of aromatic rings and molecular weight [9]. Chrisman [10] illustratively state that the appearance of asphaltene which is more blackish and amorphous. Formation or occurrence of asphaltene precipitation in crude oil is mainly because of factors such as high content of asphaltene and pressure difference between bubble point pressure and reservoir pressure. High atomic ratio carbon or hydrogen, higher condensed of aromatic rings and high aromaticity is the main feature that observed in the precipitation of asphaltene in crude oil [10]. Chromatographic techniques like SARA fractionation is used for hydrocarbon group determination. Asphaltene will flocculate and turn into solid deposits if the ratio of aromatics to saturates decrease [11]. Asphaltene flocculation will cause solid precipitation in pipelines. Even if the process of flocculation is reversible thermodynamically, the size of asphaltene flocs which tend to look bigger in size and its adsorption affinity to solid surfaces makes it harder for the process to happen [12].

Chemical injection method proves to be an efficient method in decreasing the wax and asphaltene precipitation in crude oil. A lot of combinations of wax and asphaltene inhibitors are suggested as chemical injection method. For the wax inhibition, usage of polymeric inhibitor proved to be useful in decreasing the wax content in crude oil [13]. Yang [14] also stated the usage of polymeric wax inhibitors such as ethyl vinyl acetate (EVA) in the transportation of waxy crude oil in pipelines. Reduction in viscosity, pour point and yield stress is proved when polymer wax inhibitor is used in a study conducted by [15]. Wang [16] stated that usage of a synthetic polymer such as Poly Octadecyl methacrylate (PODMA) could reduce the wax inhibition by 50% even though it has no effect on heavy paraffin such as C_{35} and above. Wax inhibitor needs a good solvent to solubilize the polymeric wax inhibitor. Methylcyclohexane (MCH) works best with the polymeric wax inhibitor [17]. The boiling point of MCH is also higher than PODMA which aids in the selectivity of the solvent.

The solubility of asphaltene in the aromatic solvent helps in the choice of an aromatic solvent. Aromatic solvents such as toluene, benzene, and xylene help in stabilizing asphaltene micelles and precipitation inhibition [18]. Asphaltene is insoluble in hydrocarbon solvents. Inhibitor IR95 has better efficiency in reducing the asphaltene precipitation. Adsorption will happen between asphaltene inhibitor and the precipitation through electrostatic and Van der Waal interaction between them [19].

This study solely aims at the investigation of flow properties of crude oil when inhibitors composed of different inhibitors are mixed together where viscosity is taken as a parameter that will be analyzed. PODMA was taken as a wax inhibitor as the reduction of viscosity reach up to 50%. MCH was used as a wax inhibitor solvent while Toluene (TOL) is used as an asphaltene solvent. This study aims at the reduction capability of viscosity using the synthetic polymer in the crude oil whereby the wax and asphaltene precipitate will be solubilized and will not make the crude oil to be more viscous. Response surface methodology RSM software was used before and after the experiments to build a model which further used to optimize the model to get an optimum ratio of inhibitors. Aspen HYSYS was used to simulate the data for the responses to be included in RSM model in order to validate the findings and to validate the experimental procedure. Several tests were carried out to show the characteristics and components inside the crude oil which are API test, C to H ratio test, DSC analysis, and FTIR analysis.

Materials and Methodology

Materials

The crude oil to be tested in this study was Malaysian crude oil, specifically taken from Sabah platform,

Malaysia. A wax inhibitor that was used for wax inhibition for this study was Poly Octadecyl methacrylate (POMA). PODMA is a synthetic polymer which aids in reducing the wax precipitation in crude oil. Heavy deposition of wax can be prevented from forming wax crystals with the help of this wax inhibitor. Wax inhibitor needs a solvent for the synthetic polymer to solubilize. An organic solvent that was used for the wax inhibitor is MCH. The melting point of the synthetic polymer (PODMA) is around 18˚C to 20˚C. Hence the boiling point for the organic solvent needed for the inhibitor must be higher than the wax inhibitor. The boiling point of MCH which reaches up to 101°C makes it is to be the suitable organic solvent for the experiment. Asphaltene inhibitor which is used for this experiment is toluene. Toluene is an aromatic solvent which makes it suitable for asphaltene because asphaltene is soluble in an aromatic solvent. Asphaltene flocculation can be reduced drastically with the use of toluene solvent. Toluene will decrease the formation of crystals of asphaltene. The crystal modifiers (PODMA) and the solvents (MCH and TOL) were obtained from Sigma Aldrich.

Viscosity Measurement

A viscometer is used to evaluate the viscosity of blank crude oil. The viscometer used was Brookfield Programmable DV-II+ Pro Viscometer. The standard settings of the equipment were the spindle size must be 63, rotational speed at 100 rpm and the units calculated for viscosity is in cP. The viscometer must be auto-zeroed before any testing of samples to get an accurate reading of the viscosity. Viscometer must be turned on left for about 10 min for the purpose of warming up the viscometer to get accurate readings. The spindle of viscometer must be handled carefully as it is very sensitive and can lead break under careless handling.

Binder oven was used to heat up the crude oil up to 90˚C for an overnight before the mixing of inhibitors. This is to melt the wax and asphaltene precipitation in crude oil. Hot plate stirrer was used to provide the perfect temperature for the mixing of the inhibitors and solvent and also during the mixing of inhibitors and crude oil. The water bath was used to provide temperature in the range of 25˚C to 40˚C during the experiments. A digital thermometer was used to check the temperature constantly with a time interval.

Experimental Procedure

The crude oil was heated at 90˚C in binder oven for an overnight before mixing of inhibitors. This is to melt the wax and asphaltene precipitation in crude oil. The preliminary step for the preparation of chemical was to heat the apparatus needed such as viscometer, measuring cylinder and pipette until 30˚C. This step is to avoid the precipitation of wax and asphaltene when the crude oil comes into contact with the cold apparatus. Before the mixture of components such as PODMA, MCH, and TOL, all the components were heated in water to increase the temperature up to 50˚C to 60˚C. Inhibitors were prepared by conducting on the hot plate at a temperature of about 90˚C. The three different components, PODMA, MCH and TOL were measured separately according to the parameter set for the conduct of this experiment. The component was measured separately respective to its volume and weight. The unit for the components is mL as the entire component used for the inhibitor is in liquid. The total volume of inhibitor used as weight percentage was 0.5 g. Hence for an example, if 40% of PODMA, 30% of MCH, 30% of TOL were used for the experiment, then, 0.2 g of PODMA, 0.15 g of MCH and 0.15 g of TOL were divided with the density of the respective components and the volume are taken after the calculations. The calculated volume of the inhibitors was measured and mixed together with the use of micropipette. The set of samples were tested for viscosity where the temperature ranges from 25˚C to 40˚C with the interval of 5˚C. The control experiment was conducted with the absence of inhibitors. Brookfield Programmable DV-II+ Pro Viscometer is used with the spindle size of 6 and rotational speed of 100 rpm.

Response Surface Method (RSM) Modeling

Before proceeding with a row of an experiment, RSM was used to get the number of the experiment to test the inhibitors with crude oil. Three parameters which are respective percentage composition of PODMA, MCH, and TOL with viscosity as a response were carried out in the RSM model. Tables 1 & 2 represents model information and factors used in RSM, respectively.

File Version	Design Expert 11.0.3.0
Study type	Response Surface
Design type	Box-Behnken
Design model	Quadratic
Subtype	Randomized
Runs	13

Table 1: Model information using RSM.

Factor	Name	Units	Type	Minimum	Maximum	Mean	Std. Deviation
A	PODMA	%	Numeric	30	50	40.0	8.2
B	TOL	%	Numeric	10	40	25.0	12.2
C	MCH	%	Numeric	25	50	37.5	10.2

Table 2: Factors used in RSM.

Table 1 shows the design model and type that is used for this design quadratic model which is Box- Behnken. The selection of this model is due to the reduction in the number of experiments compare to factorial 3^3 design which the number of runs/experiments are 27 for 3 variable optimization. For the Box-Behnken model, the numbers of run/experiments are 13. The selection of this design is economical and efficient [20]. Three factors have been used for this design which is A: PODMA, B: TOL, C: MCH. Total of 13 samples is tested at a different temperature which in the range from 25˚C to 40˚C. The parameter that would take from experimental data to become responses for RSM would be the viscosity of the 13 samples. The samples are prepared according to the percentage of the composition obtained from RSM design.

Simulation Using Aspen HYSYS

Two sets of data were calculated and the readings are used for the design of RSM model. The readings are taken from Aspen HYSYS and implemented into RSM to validate the experimental procedure and methods. Table 3 shows the data and parameters set for case in Aspen HYSYS before calculating the viscosity.

Components	n-C4Sterate
	TOL
	MCH
	Hypo Component (Crude oil)
	n-C4Sterate
Fluid package	Wilson
Vapor model	Peng Robinson
Temperature	25˚C - 40˚C
Pressure	1 atm
Molar flow	500 kg mole/h
Compositions	Depends on the calculation based on the data derived from RSM model.

Table 3: Data needed to enter simulation environment.

Apart from TOL and MCH, the other two components were not available in Aspen HYSYS. Hence for PODMA, the component which has physical properties the same as PODMA was chosen. For crude oil, a hypo component needed to be created as there is no existing component which has the same physical properties as crude oil. Wilson was chosen for Fluid package as it is the best fit to be used as fluid package for mixture classifications as hydrocarbons and aromatics. The temperature range was taken by referring the WAT.

Results and Discussion

Characterization of Blank Crude Oil

Characterization of blank crude oil was analysed before conducting experiments. This was to make sure the suitability of the crude oil needed to test the samples for the experiments before it is conducted.

Blank Crude Oil Properties

API gravity reading is very important in identifying the classes of crude oil. API gravity for blank crude oil was 44.5˚ which falls under very light crude oil category. Carbon to hydrogen ratio analysis was to show the abundance of hydrogen compounds in a petroleum-based compound. Calculation of carbon to hydrogen ratio in blank crude oil would give a value of energy content of the crude oil. Carbon to hydrogen ratio was found to be 6.17. The crude oil is not as efficient as the content of hydrogen in much lower compared to carbon content.

Digital Screening Calorimetry (DSC) Analysis

Digital Screening Calorimetry analysis plays a vital role in identifying the WAT. The DSC analysis shows the WAT of the blank crude oil to be at 46.25˚C. By this specific temperature value, the temperature range in conducting the experiment is fixed which is around 30˚C to 50˚C for all the samples.

Fourier Transform Infrared Spectroscopy (FTIR) Analysis

FTIR analysis is described as analysis carried out by infrared spectroscopy. The FTIR spectroscopy is all about the analysis involving vibrational excitation of molecular bonds of a sample by absorption of infrared light energy. The addition of vibrational spectra can create an infrared absorption spectrum which will look in peaks of molecular fingerprint of the tested sample [21]. Figure 1 shows the FTIR analysis on blank crude oil and it clearly

proves the presence of wax paraffin. Wax paraffin is proved with the presence of C-H and C-C bonding. Saturated hydrocarbons peaks will be in the range of 1377 to 1461cm^{-1}. The region in between the interval of 400 to 1000cm^{-1} shows the aromatic bonds found in the blank crude oil [7]. The absorbance present which is 455.03cm^{-1},481.17cm^{-1} and 739.67cm^{-1} is due to the aromatic CH out of plane bending vibrations. The stretching mode of C-H bonds also shows strong absorption between 2852 cm^{-1} to 2922.39cm^{-1}. The FTIR analysis concluded the presence of abundant wax and asphaltene in the crude oil.

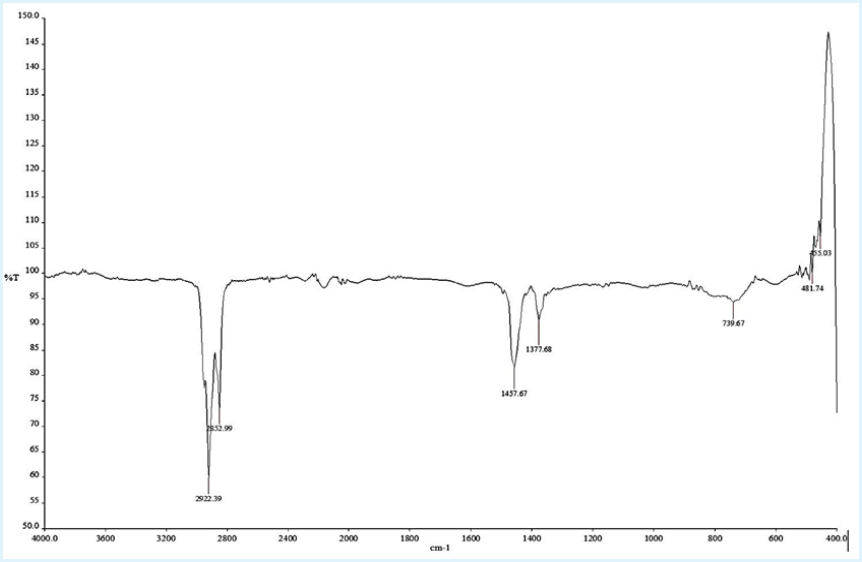


Figure 1: FTIR analysis of blank crude oil.

The reading of peaks in the analysis is correlated to the one from the literature reviews. Table 4 shows a comparison between two different samples.

Peaks Showing the Presence of Wax in Crude Oil, cm^{-1} (Wu and Kessler, [22])	Peaks in the FTIR Analysis of Sabah Blank Crude Oil, cm^{-1}
1458	1457.67
1375	1377.68

Table 4: Values of a peak in two different samples.

Viscosity of Blank Crude Oil

Viscosity of the blank crude oil which acts as a control sample is measured and the data is shown in Figure 2. The viscosity of the sample is measured in different temperatures but in accordance with the WAT which is from 25˚C to 40˚C range.

Figure 2 shows that the viscosity of crude oil gradually increases when the temperature is decrease. The crude oil tends to lose its flow properties in lower temperature.

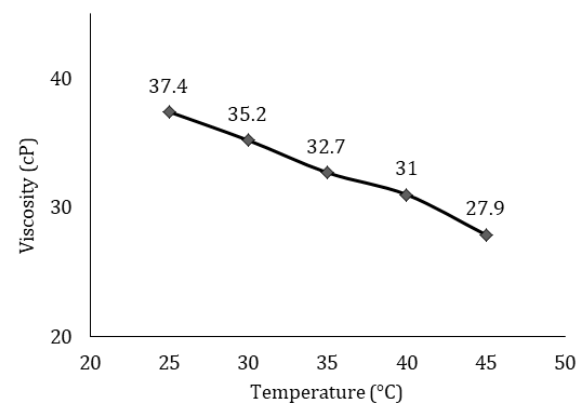


Figure 2: Viscosity of blank crude oil in different temperature.

Viscosity Reduction Analysis

The set of experimental data proves that the viscosity of the crude oil tends to increase when the temperature of the samples decreases. This can be observed from the

Figures 3-5. The reduction of viscosity in the crude oil is composed of different inhibitors percentages of composition in a range of temperatures.

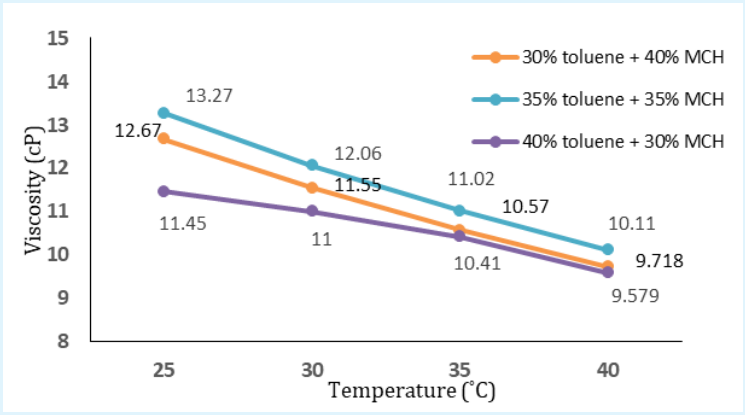


Figure 3: Viscosity of fixed 30% PODMA and crude oil against temperature

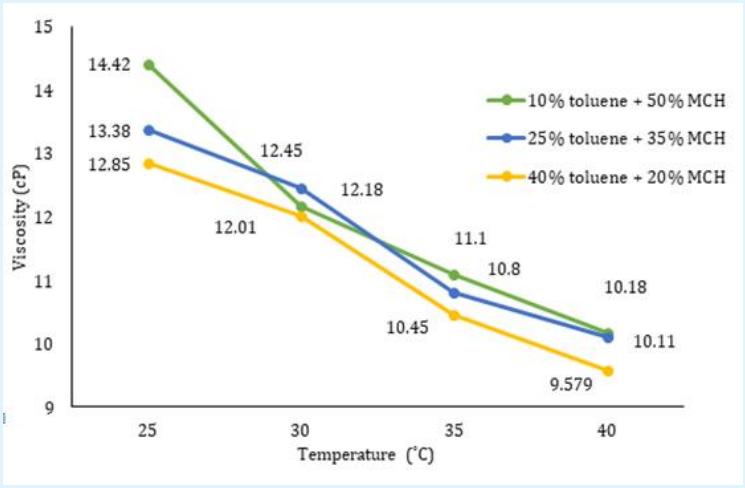


Figure 4: Viscosity of fixed 40% PODMA and crude oil against temperature.

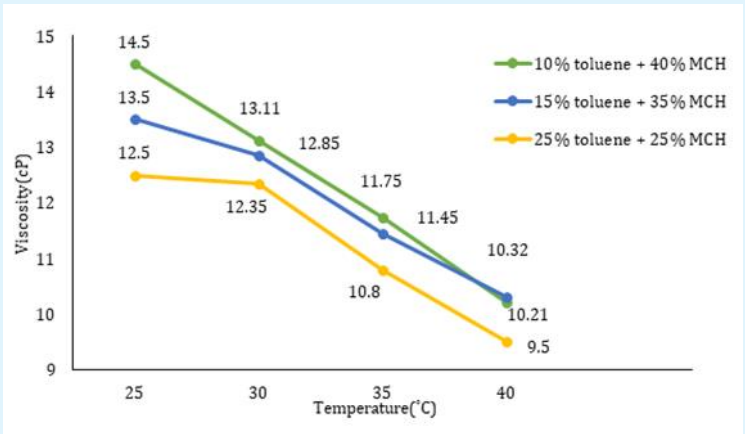


Figure 5: Viscosity of fixed 50% PODMA and crude oil against temperature.

PODMA (%)	The Optimum Amount of TOL and MCH (% TOL: % MCH)	Viscosity Reduction (%)
30	30:40	64-69
	35:35	
	40:30	
40	10:50	62-64
	25:35	
	40:20	
50	10:40	61-66
	15:35	
	25:25	

Table 5: Summary of the viscosity of crude oil from experimental data.

Table 5 shows the summary of the viscosity of crude oil from experimental data

From the Table 5, the results show that the greater reduction in viscosity at lower ratio of PADMA. Samples which contain a high percentage of toluene tend to decrease the viscosity of sample specifically in 25˚C. This is due to the increment of solubility of asphaltene in crude oil which is due to the presence of TOL re-dissolves the asphaltene precipitation. TOL molecules act as a solvent which disrupts the asphaltene entanglement process. This is will occur through interfering into $\pi - \pi$ interactions between aromatic rings around the asphaltene precipitate [23]. The ratio of MCH component is not really affecting the reduction of viscosity. The sole purpose of the solvent is to act as a solvent for wax inhibitor.

Comparison and Analysis of Data Using RSM Model

The 13 experiments are carried out and the readings are taken and tabulated. The readings of viscosity for the optimization of the Box-Behnken model considered to be taken only for the samples measured at 25˚C. This is because the wax and asphaltene will start to precipitate in lower temperature. As per DSC analysis, the WAT of blank crude oil is at 46˚C. No significant reduction of viscosity is present in the results of the samples at 30˚C and above. Hence, viscosity readings measured at 25˚C is taken for the response in RSM. The viscosity readings from the Aspen HYSYS are also taken as the response for another RSM model. Tables 6 & 7 show the responses to the experimental data and HYSYS data, respectively.

Standard Run	Run	Factor 1 A: PODMA (%)	Factor 2 B: TOL (%)	Factor 3 C: MCH (%)	Response 1 Viscosity (cP)
1	12	30	10	37.5	13.32
2	2	50	10	37.5	14.50
3	6	30	40	37.5	11.45
4	11	50	40	37.5	13.43
5	13	30	25	25	13.27
6	1	50	25	25	14.42
7	7	30	25	50	12.46
8	9	50	25	50	13.46
9	4	40	10	25	14.57
10	10	40	40	25	13.34
11	3	40	10	50	13.42
12	8	40	40	50	12.67
13	5	40	25	37.5	13.38

Table 6: Responses of experimental data.

Standard Run	Run	Factor 1 A: PODMA (%)	Factor 2 B: TOL (%)	Factor 3 C: MCH (%)	Response 1 Viscosity (cP)
1	12	30	10	37.5	13.15
2	2	50	10	37.5	14.15
3	6	30	40	37.5	12.44
4	11	50	40	37.5	13.43
5	13	30	25	25	13.03
6	1	50	25	25	14.12
7	7	30	25	50	12.45
8	9	50	25	50	14.08
9	4	40	10	25	14.5
10	10	40	40	25	13.05
11	3	40	10	50	13.42
12	8	40	40	50	12.37
13	5	40	25	37.5	13.08

Table 7: Responses of HYSYS data.

The following responses are entered in two different models with the same model, type and runs. Analysis of variance (ANOVA), Fit Statistics, Actual equation, 3-D interaction together with one-factor interaction are discussed for both the responses shown in the Tables 6 and 7.

Development of Regression Model Equations Using Box-Behnken Model

Referring to the earlier design, the inhibitors were prepared based on the combination of three chemicals such as PODMA, TOL, and MCH. The ratio of combination is taken from the help of RSM model. The response taken is the measurement of viscosity when inhibitors combined with blank crude oil. ANOVA is used to determine the regression model equation for the Box-Behnken design. The model used for both RSM involving experimental and HYSYS data is reduced two Factor Interaction (FI), model. The reduced 2FI is taken into consideration as this model explains the interaction between two components which show significant p-value. Despite, that the model used Box-Behnken design is used to have sets of 13 run of experiments to identify significant results from the set of experiments.

$$Viscosity\ (experimental) = 16.40064 - 0.095750A + 0.006917B - 0.094033C + 0.003540AC - 0.001467BC \quad (1)$$

$$Viscosity\ (HYSYS) = 16.10058 + 0.000750A - 0.063500B - 0.117600C + 0.001760AC + 0.000800BC \quad (2)$$

Equation (1) represents the actual equation of experimental data whereas Equation (2) represents the actual equation of HYSYS data. Each term in the equation above represents such as: A is ratio percentage of PODMA, B is ratio percentage of TOL and C is ratio percentage of MCH.

Statistical Analysis of Variance (ANOVA) for the Viscosity

Statistical analysis for this experiment dependant on ANOVA analysis. The analysis can be done by studying on the p-value, R^2, and adjusted R^2. The analysis was tabulated as in Table 8 based on the ANOVA for both experimental data and HYSYS data.

Table 8 shows the Model F-value of 6.81 which implies the model is significant. P-value which lower than 0.05 proves that the model is significant. P-value of the model indicates the chance of 1.28% chance that an F-value this large could occur due to disturbance. From the analysis, it shows that Factor A which is the ratio percentage of PODMA and Factor B which is the ratio percentage of TOL is the significant model terms. Table 9 shows the Fit statistics of ANOVA model for experimental data.

Source	Sum of Squares	DF	Mean Square	F-value	P-value Prob >F	
Model	6.49	5	1.3	6.81	0.0128	Significant
A-PODMA	1.1	1	1.1	5.74	0.0477	
B-TOL	4.16	1	4.16	21.83	0.0023	
C-MCH	0.1485	1	0.1485	0.7790	0.4067	
AC	0.7832	1	0.7832	4.11	0.0823	
BC	0.3025	1	0.3025	1.59	0.2482	
Residual	1.33	7	0.1907			
Cor Total	7.83	12				

Table 8: Statistical analysis of variance for the experimental data

Statistics	Values
Std. Deviation	0.4366
Mean	13.15
C.V.%	3.32
R^2	0.8295
Adjusted R^2	0.7076
Predicted R^2	0.2978
Adequate precision	7.4965

Table 9: Fit statistics of ANOVA model for experimental data.

Table 9 shows the predicted R^2 of 0.2978 which is not as close to the adjusted R^2 of 0.7076. The difference is more than 0.2. This may indicate a large block effect or a possible problem with model and/or data. The mean value of from the set of data is 13.15 and the standard deviation of the set of data is 0.4366. The value of adequate precision lies at 7.4965. Adequate precision measures the signal to noise ratio. A value greater than 4 is desirable. Hence this model can be used to navigate the design space. Table 10 shows the statistical analysis of variance for HYSYS data.

Source	Sum of Squares	DF	Mean Square	F-value	P-value Prob >F	
Model	6.79	5	1.36	20.69	0.0005	significant
A-PODMA	3.56	1	3.56	54.29	0.0002	
B-TOL	2.02	1	2.02	30.77	0.0009	
C-MCH	0.9248	1	0.9248	14.09	0.0071	
AC	0.1936	1	0.1936	2.95	0.1296	
BC	0.0900	1	0.0900	1.37	0.2800	
Residual	0.4596	7	0.0657			
Cor Total	7.25	12				

Table 10: Statistical analysis of variance for HYSYS data.

Referring the Table 10, Model F-value of 20.69 implies the model is significant. P value which lower than 0.05 proves that the model is significant. P-value of the model indicates the chance of 0.05% chance that an F value this large could occur due to disturbance. From the analysis, it shows that Factor A which is the ratio percentage of PADMA, Factor B which is ratio percentage of Toluene and Factor C which is ratio percentage of MCH is the significant model terms. Table 11 shows the Fit statistics of ANOVA model for HYSYS data

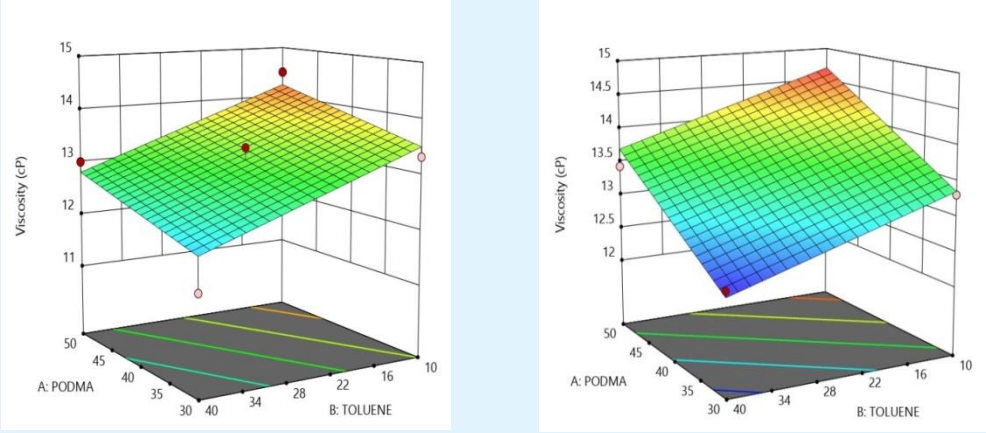
Statistics	Values
Std. Deviation	0.2562
Mean	13.52
C.V.%	1.89
R^2	0.9366
Adjusted R^2	0.8914
Predicted R^2	0.7152
Adequate precision	13.7729

Table 11: Fit statistics of ANOVA model for HYSYS data.

The predicted R^2 of 0.7152 is in reasonable agreement with the Adjusted $R^2$of 0.8914 where the difference is less than 0.2. The mean value of from the set of data is 13.52 and the standard deviation of the set of data is 0.2562. The value of adequate precision lies at the desired value which is 13.7729.

Interaction between Components

Figures 6 (a,b) shows the 3-D Illustration of experimental data and HYSYS data, respectively.

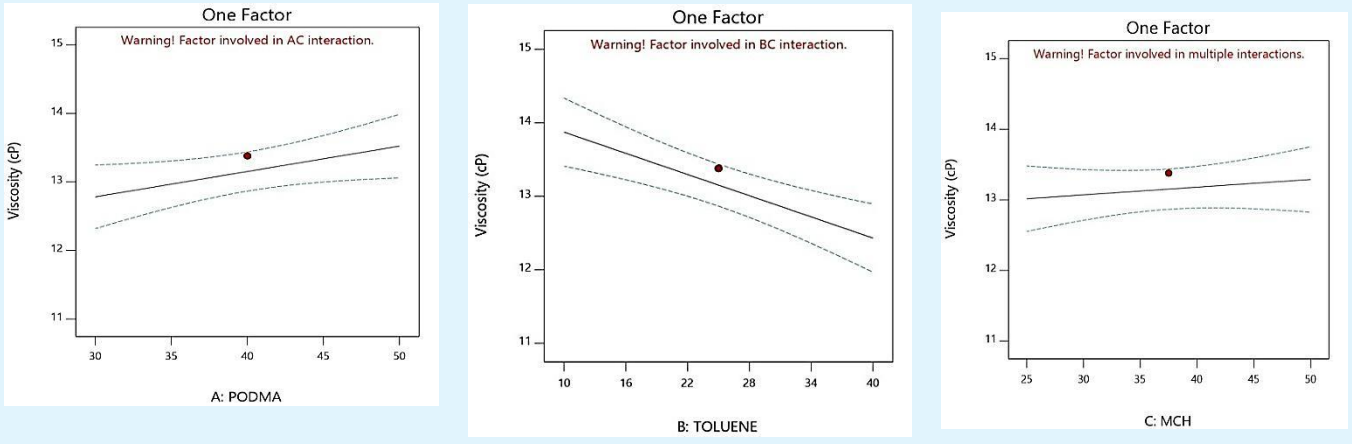


(a) (b)

Figures 6: 3-D Illustration of (a) experimental data (b) HYSYS data

Figure 6(a) shows higher level of reduction in viscosity at the point where the 3d graph shown in slight blue for the experimental data. Viscosity reduction seems to be lower in the region marked red in the graph. Figure 6(b) proves that the values obtained from HYSYS simulation is perfect as low amount of viscosity is recorded in the blue region compared to the 3-D illustration of experimental data.

Figure 7 (a, b & C) shows the one-factor interaction between specific components with viscosity for experimental data.

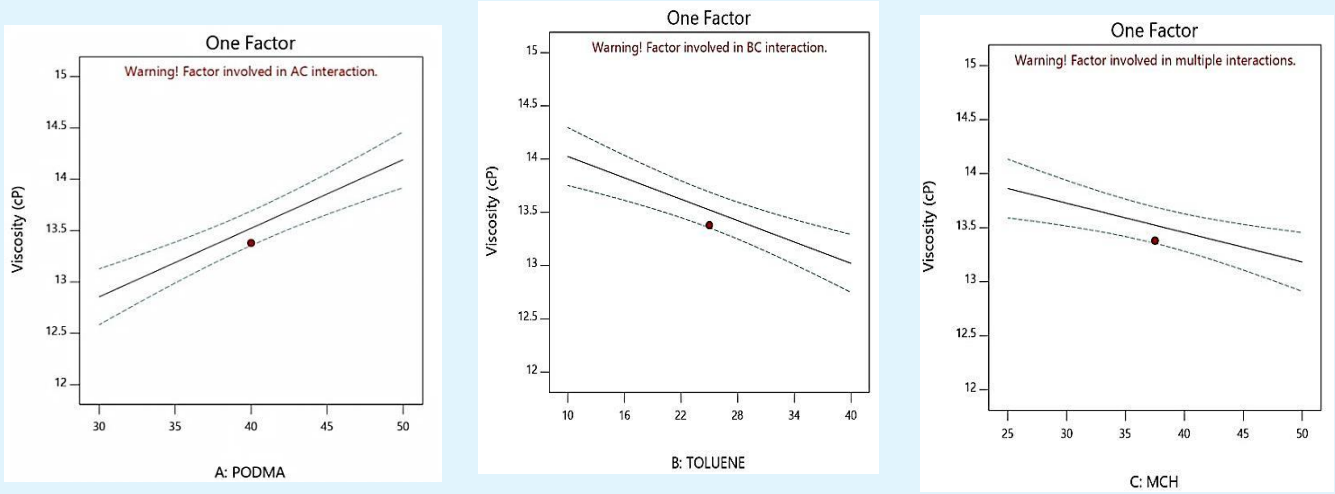


(a) (b) (c)

Figure 7: (a) The interaction between PODMA and viscosity for experimental data (b) The interaction between TOL and viscosity for experimental data (c): The interaction between MCH and viscosity for experimental data.

Figure 7 (a) shows that lower amount of PODMA in the percentage composition of inhibitor could reduce the viscosity whereas Figure 7 (b) proves that the surge in the ratio of composition of TOL in inhibitor would decrease the viscosity reading. Figure 7 (c) shows the composition ratio of MCH in inhibitor not really affects the viscosity readings as it didn't show any significant change.

Figure 8 (a, b & C) shows the one-factor interaction between components for HYSYS data



(a) (b) (c)

Figure 8: (a) The interaction between PODMA and viscosity for HYSYS data (b) The interaction between TOL and viscosity for HYSYS data (c) The interaction between MCH and viscosity for HYSYS data.

Figure 8 (a) shows the one-factor interaction between PODMA and viscosity for HYSYS data. The viscosity of crude oil with inhibitor tends to increase when the composition percentage of PODMA increase. For Figure 8 (b), the viscosity of crude oil with inhibitor decrease when the composition percentage of TOL increases. Figure 8 (c) shows a slight drop in viscosity when the percentage composition of MCH increases.

The two RSM model has compared accordingly. The HYSYS data for responses for RSM is too perfect as the data is generated with the aid of software. The trend in the interaction between both components in aligns except for the interaction between viscosity and MCH. But this is neglected as it is incorporated by the uncertain data input in Aspen HYSYS simulation environment. The experimental procedures and materials used are validated using Aspen HYSYS.

Optimization of Percentage Composition of PODMA, MCH, and TOL using Response Surface Method (RSM)

The main purpose of the optimization is to identify the perfect percentage composition involving all the components for the reduction of viscosity. Besides that the optimization is also used for determination of minimum viscosity achievable for the crude oil with inhibitor. Table 12 shows the optimization of the ratio of components towards viscosity

Type of components	Goal	Value of optimization
PODMA (%)	In range	30
MCH (%)	In range	40
TOL (%)	In range	50
The viscosity of crude oil (cP)	Target	11.45
Desirability	0.997	

Table 12: Optimization of the ratio of components towards viscosity.

Table 12 shows the optimum ratio of components needed to reach minimum viscosity using a numerical method. The minimum viscosity that can be achieved at 25˚C is 11.45 cP when the ratio of PODMA is 30%, MCH is 40% and TOL is 50%.

Conclusion

In conclusion, the first and utmost objective of this study is achieved as inhibitor composed of PODMA, MCH and TOL which show the significant effect in improving the flow properties of crude oil by reducing the viscosity of crude oil. The wax inhibitor, PODMA, and asphaltene inhibitor, TOL play a vital role in reducing the viscosity of crude oil. Furthermore, another objective is also achieved by validating the experimental data and procedure. The ANOVA, statistical data and interaction graph aided by the use of RSM proof of the validation of experimental data and procedure. The comparison of data between two models of responses from experimental and HYSYS data further strengthen the novelty of this research paper even though one interaction involving a component is not aligned between both of the models. But this is due to the uncertainty of data input for two components in Aspen HYSYS as there is no existence of data in Aspen database. Finally, the last objective is achieved when the optimized percentage ratio of components in an inhibitor is obtained. The optimized ratio from RSM is 30% for PODMA, 40% for TOL and 50% for MCH. This result is further strengthened by experimental data as the inhibitors with 30% PODMA composition show a greater reduction of viscosity compared to others.

Acknowledgment

The authors would like to express the greatest appreciation to the Centre of Research and Innovation (PPI), Universiti Malaysia Sabah (UMS) for the support of this study (Grant No. SBK0346-2017).

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