

Evaluation of One Factor at A Time (OFAT) Technique in Viscosity Modeling of Polymer Solution

¹Saeed Akbari, ¹S.M. Mahmood, ²Isa M. Tan and ³Bamikole J. Adeyemi

¹Department of Petroleum Engineering, Center of Enhanced Oil Recovery,

²Department of Fundamental and Applied Science,

³Department of Petroleum Engineering, Universiti Teknologi Petrona, Perak, Malaysia

Abstract: Viscosity has been identified as the main solution property in polymer flooding applications. Currently UTCHEM simulator is claimed to be more robust than CMG-STARs and ECLIPSE, since it takes into account salinity and hardness effects on polymer viscosity other than polymer concentration and shear rate effects. However, UTCHEM model was developed using One-Factor-at-A-Time (OFAT) approach. The major disadvantage of the OFAT strategy is that it fails to consider any possible interactions between the factors. In this research, it has been showed that interactions between factors in polymer studies are very common and they lead to producing poor results by OFAT strategy and consequently by the viscosity model. This study evaluates the viscosity model of UTCHEM simulator for predicting bulk viscometric data. UTCHEM Model was compared to experimental data to evaluate its predictive accuracy. Although, UTCHEM Model accurately predicted polymer viscosity at zero shear rate, it gave inaccurate results at increased shear rate. Results showed that there exist interaction among the various factors involved in polymer studies. Consequently, Design Of Experiment (DOE) is proposed for improved model for predicting polymer viscosity.

Key words: UTCHEM, polymer flooding, viscosity, One Factor at A Time (OFAT), Design Of Experiment (DOE), Perak

INTRODUCTION

Polymer flooding has been applied commercially for over four decades. Polymers are added to injected fluid front for maintaining mobility control and ultimately increase recovery. This practice has been adopted during several improved/Enhanced Oil Recovery (EOR) and water control projects. Polymer solutions are complex since polymer flexible macromolecules will be affected by solution condition. Addition of polymer leads to high viscosity and enhanced stability. The resulting solutions are polymer-thickened which facilitates effective mobility control during enhanced oil recovery processes. This is an important step towards achieving the ultimate goal of polymer flooding which is aimed at decreasing the mobility of injected water and increasing its sweep efficiency (MacWilliams *et al.*, 1973; Luo *et al.*, 2006).

Polymer solutions assume both newtonian and non-newtonian properties at different stages of flow. They typically exhibit newtonian behavior at very low share rate and at very high shear rates. Additionally, a region of shear thinning where the viscosity of the fluid decreases exists at moderate share rates. Viscosity share

rate relationship ($\dot{\gamma}$) has been empirically modeled in one or more of these regions by several researchers (Carreau, 1972; Meter and Bird, 1964). Power law model which describes the pseudoplastic region is undoubtedly the commonly applied analytical form of $\eta(\dot{\gamma})$. This model is also sometimes referred to as the law of Ostwald and Waele expressed as:

$$\eta(\dot{\gamma}) = K(\dot{\gamma})^{n-1} \quad (1)$$

where, K and n are constants. For a Newtonian fluid, $n = 1$ and K is simply the constant viscosity, μ . This expression, Eq. 1, describes the pseudoplastic region quite satisfactorily but not suitable at high and low shear rates. Meter and Bird (1964) presented a more satisfactory model. Meter's equation assumes that the polymer viscosity at infinite shear rate (μ_∞) is equal to the water viscosity. Subsequently, Carreau equation has been reported as a more general model for these shear regimes since it gives a much improved fit to viscosity/shear rate data (Carreau, 1972; Chauveteau, 1982). Carreau equation expresses viscosity function as:

$$\eta(\dot{\gamma}) = \eta_\infty + (\eta_0 - \mu_\infty) \left[1 + \left(\lambda \dot{\gamma} \right)^{(n-1)/2} \right] \quad (2)$$

where, $\eta_{\infty}, \eta_0, \lambda$ and n are infinite shear rate viscosity, zero shear rate viscosity, a time constant and a fitting parameter, respectively. Despite giving an improved fit to viscometric data over a wide range of shear rates, Carreau equation requires four parameters as opposed to the power law's two. Besides, it renders particular analytical calculations involving viscosity function much more difficult.

The various approaches to the mathematical modeling of non-Newtonian rheology (the flow behavior of non-Newtonian fluids) in porous media have been applied by different researchers. These studies became necessary to relate the flow behavior of polymer solution within porous media, commonly known as the in-situ rheology, to the bulk fluid viscometric data. Meanwhile, an important parameter needed to achieve sufficient estimation of polymer solution rheology in the porous media is equivalent shear rate. Pseudo-Darcy law can be used to calculate equivalent shear rate within the porous media. Subsequently, in-situ viscosity is estimated by substituting shear rate in the equation for calculating the bulk fluid viscosity for equivalent shear rate. Thus, modeling the viscometric properties of bulk fluid is the first and critical step towards accurate estimation of in-situ viscosities in porous media.

Economic potential of polymer flood is mostly determined by simulation and has been studied by many researchers. Several commercial reservoir simulators such as CMG-STARs, ECLIPSE and the University of Texas Chemical Flooding Simulator (UTCHEM) are available for modeling these complex EOR processes. UTCHEM simulator has been claimed to be more robust than others, since it takes into account salinity and hardness effects on polymer viscosity other than polymer concentration and shear rate effects. Polymer solution is assumed to be shear-thinning (pseudoplastic) non-Newtonian fluid in UTCHEM and many other reservoir simulators. This behavior was modeled in UTCHEM using the Meter equation (Meter and Bird, 1964). However, One Factor at A Time (OFAT) approach was used to develop the bulk fluid viscosity model in UTCHEM by evaluating each parameter across a range of values while keeping other parameters constant.

Biopolymers, e.g., Xanthan and synthetic polymer, e.g., HPAM have been used for actual polymer flooding processes. Literature shows that process variables such as polymer concentration, shear-rate, salt concentration, temperature, pH and molecular weight influence polymer solution viscosity (Luo *et al.*, 2006; Rashidi *et al.*, 2010). Both Xanthan and HPAM are called polyelectrolytes, since they have multiple charges distributed along their

chains. In general, polyelectrolytes are distinguished from non-ionic polymers by the large effects which changes in salt concentration and pH have on their viscosity.

In this study, a review of UTCHEM Model is presented to reveal the accuracy of OFAT approach in predicting bulk fluid viscosity of polymer solutions. Its predictive capability was examined and evaluated using experimental data.

Polymer solution viscosity calculation (UTCHEM Model): At low (near zero) shear rate, the viscosity of polymer solution is calculated as a function of polymer and electrolyte concentrations. UTCHEM Model uses the modified Flory-Huggins equation as follows:

$$\mu_p^0 = \mu_w \left(1 + \left(A_{p1} C_p A_{p2} C_p^2 + A_{p3} C_p^3 \right) \right) C_{SEP}^{sp} \quad (3)$$

Where:

A_{p1}, A_{p2} and A_{p3} = The empirical constants which are deduced from experimental data for a given polymer

C_{SEP} = The effective salinity

It is used in polymer property calculations and defined as:

$$C_{SEP} = \frac{C_5 + \beta_p C_6}{C_1} \quad (4)$$

Where:

C_5, C_6 and C_1 = The anion, divalent and water concentrations in the aqueous phase

β_p = The parameter used to determine the effects of divalent cations on the effective salinity for polymer and it is measured in the laboratory

It is extensively acknowledged that the drastic effect of multivalent cations on polymer properties when present is more when compared with the impact of sodium ions. This effect is more pronounced for partially hydrolyzed polyacrylamide polymers than for polysaccharides such as xanthan gum. The effect of both monovalent and divalent cations are equal when $\beta_p = 1$. However, the effect of divalent cations on polymer properties is stronger when $\beta_p > 1$. The term sp is an input parameter for determining polymer viscosity as a function of salinity. It is given by the log-log plot of $\mu_p^0 - \mu_w / \mu_w$ versus C_{SEP} which is assumed to be a straight line.

The polymer viscosity at low shear rate μ_p^0 as calculated from Eq. 3 becomes an input parameter for estimating the viscosity at higher shear rate. The effect of shear rate on polymer viscosity is modeled by Meter and Birds (1964) equation and it is given by:

$$\mu_p = \mu_w + \frac{\mu_p^0 - \mu_w}{1 + \left(\frac{\dot{\gamma}}{\dot{\gamma}_{1/2}} \right)^{p_\alpha - 1}} \quad (5)$$

Where:

$\dot{\gamma}_{1/2}$ = The shear rate at which viscosity is the average of μ_p^0 and μ_w
 p_α = An empirical coefficient

Polymer viscosity is highly dependent on shear. If flow behavior in porous media is described using bulk viscosity measured at various shear rates, then, calculating the equivalent shear rate to that in the bulk viscometer is necessary. This is denoted as the in-situ shear rate and it is modeled by the modified Blake Kozeny capillary bundle equation as expressed in Eq. 6:

$$\dot{\gamma}_{eq} = \frac{\dot{\gamma}_c |\bar{\mu}_w|}{\sqrt{k k_{rw} \phi S_w}} \quad (6)$$

Where:

$\dot{\gamma}_c (s^{-1})$ = An empirical shear rate coefficient from lab experiments
 $\bar{k}, k_{rw}, \phi, S_w$ and $\bar{\mu}_w$ = Average permeability, relative permeability of the water, porosity, water saturation and water phase velocity

MATERIALS AND METHODS

UTCHEM Model evaluation: Experimental data used in this research were obtained from Yerramilli. The rheological data was imported into the modified Flory-Huggins model for a polymer solution with a salinity of 20 g/L NaCl. The fitting parameters in the Flory-Huggins Eq. 3 were determined and thereby tested for two other lower salinities of 5 and 10 g/L NaCl.

From the rheology measurements at different salinities the value of 'sp' in Eq. 3 was obtained initially and with the help of the Flory's model the viscosity dependence of concentration at zero shear rate was modelled. The viscosity measurements were modelled with the Flory's equation for different concentrations from 500-5000 ppm.

To examine and compare the accuracy of model, the performance of the model in viscosity forecasting was evaluated using four well-known statistical measures, namely Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), Sum of Squared Errors of prediction (SSE) and the coefficient of determination (R^2), which are defined as follows:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (\mu_{pred} - \mu_{exp})^2} \quad (7)$$

$$MAPE = \frac{1}{n} \sum_{i=1}^n \left| \frac{\mu_{pred} - \mu_{exp}}{\mu_{exp}} \right| \times 100 \quad (8)$$

$$SSE = \sum_{i=1}^n (\mu_{pred} - \mu_{exp})^2 \quad (9)$$

$$R^2 = 1 - \frac{\sum_{i=1}^n (\mu_{pred} - \mu_{exp})^2}{\sum_{i=1}^n \left(\mu_{pred} - \left(\frac{1}{n} \sum_{i=1}^n \mu_{exp} \right) \right)^2} \quad (10)$$

Where:

μ_{pred} and μ_{exp} = Forecasted and observed polymer solution viscosity
 n = The number of data in data set

To make statistical measures free from of dimension, each set of observed and prediction value was normalized by max value between zero and 1 first and after that error index was evaluated.

The polymer solution viscosity at different shear rates for 3000 ppm concentration were plotted to derive p_α and $\dot{\gamma}_{1/2}$ from Eq. 5. With the obtained two fitting parameter Sp_α and $\dot{\gamma}_{1/2}$ model prediction was evaluated for different polymer concentration (1000, 2000, 4000 and 5000ppm) at same salinity. The performance of the UTCHEM Model was also verified using the fitting parameters at different polymer solution salinity (10 and 5g/L).

RESULTS AND DISCUSSION

The fitting parameters, Ap_1 , Ap_2 and Ap_3 as obtained using Eq. 3 are 126.6, 15545.18 and 14105109.8, respectively. In that case, $Csep$ is 20 g/L; the water viscosity is 1 mPa.s and Sp is -0.639. Figure 1-3 show the polymer viscosity at zero shear versus polymer concentration. Good curve fit was achieved using same AP 's for the other two sets of data at different constant salinities, i.e., 10 and 5 g/L. This shows that the modification of Flory-Huggin theory in order to take into account salinities effect at zero shear rate works well since the second set of data at different constant salinity produced good curve fit using the same values of AP_1 , AP_2 and AP_3 previously generated with the data obtained with $Csep$ of 20 g/L.

The two fitting parameters p_α and $\dot{\gamma}_{1/2}$ in Eq. 5 were determined to be 1.687 and 190 sec^{-1} , respectively at

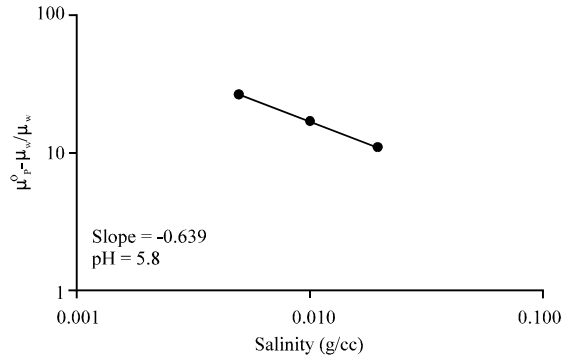


Fig. 1: Log-log plot based on Eq. 3 to calculate exponent (Sp) for divalent (calcium) to calculate C_{sep} for polymer concentration of 3000 ppm

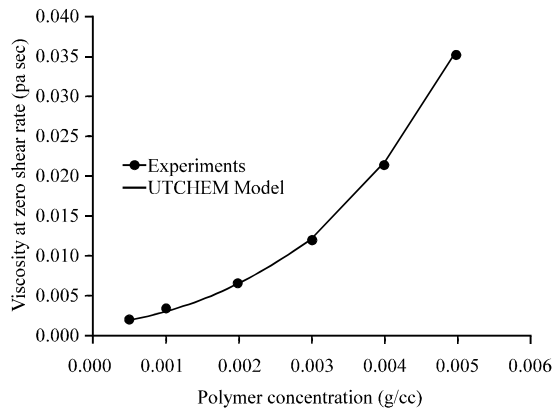


Fig. 2: Experimental data fitted with modified Flory-Huggins Model for a salinity of 20 g/L NaCl

3000 ppm polymer concentration. However, these values did not generate accurate curve fitting between the UTCHEM model and the experimental data. The deviations in viscosity response to shear rate increased as the polymer concentration moved (plus or minus) away from 3000 ppm. Figure 5 shows the plots of the polymer viscosity versus shear rate. For instance, comparing Parts A and B in Fig. 5 reveals that MAPE's value increased from 9.53-10.82 when polymer concentration reduced from 2000-1000 ppm. Same increasing in MAPE's value observed when polymer concentration was increased from 4000-5000 ppm, refer to Parts C and D in Fig. 2-4.

UTCHEM Model was developed to take into account the effect of salinity and hardness in predicting polymer solution viscosity, since CMG-Star and Eclipse Models do not consider such input parameters. Different effective salinities and polymer concentration have been determined and model prediction has been evaluated,

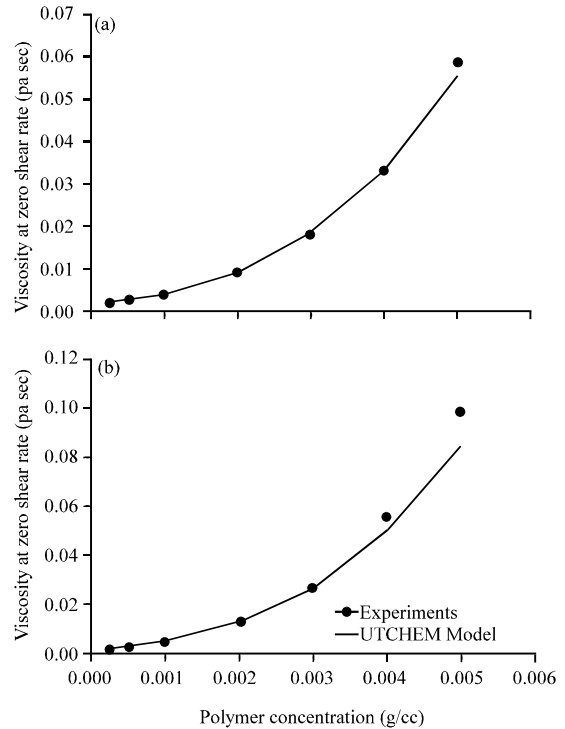


Fig. 3: Experimental data fitted with modified Flory-Huggins Model for a salinity of: a) 10 g/L NaCl and b) 5 g/L NaCl

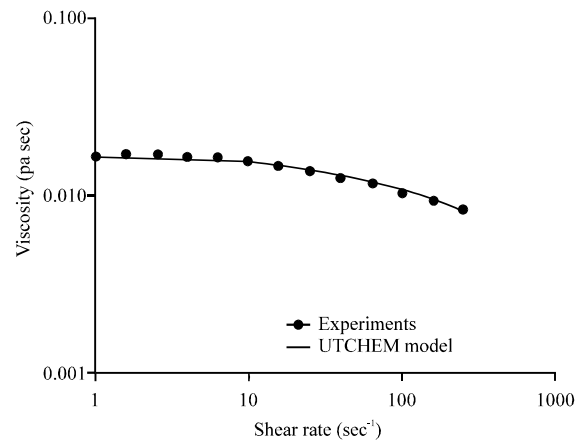


Fig. 4: Best curve fit polymer viscosity vs shear rate at constant salinity of 10 g/L NaCl and polymer concentration of 3000 ppm; Error evaluation: SSE = 0.0118; $R^2 = 0.97202$; RMSE = 0.03010; MAPE = 3.40905

refer to Fig. 6. Error associated with the modelling of experimental data is evaluated using statistical measures and projected in the relevant figure. Failingly, model

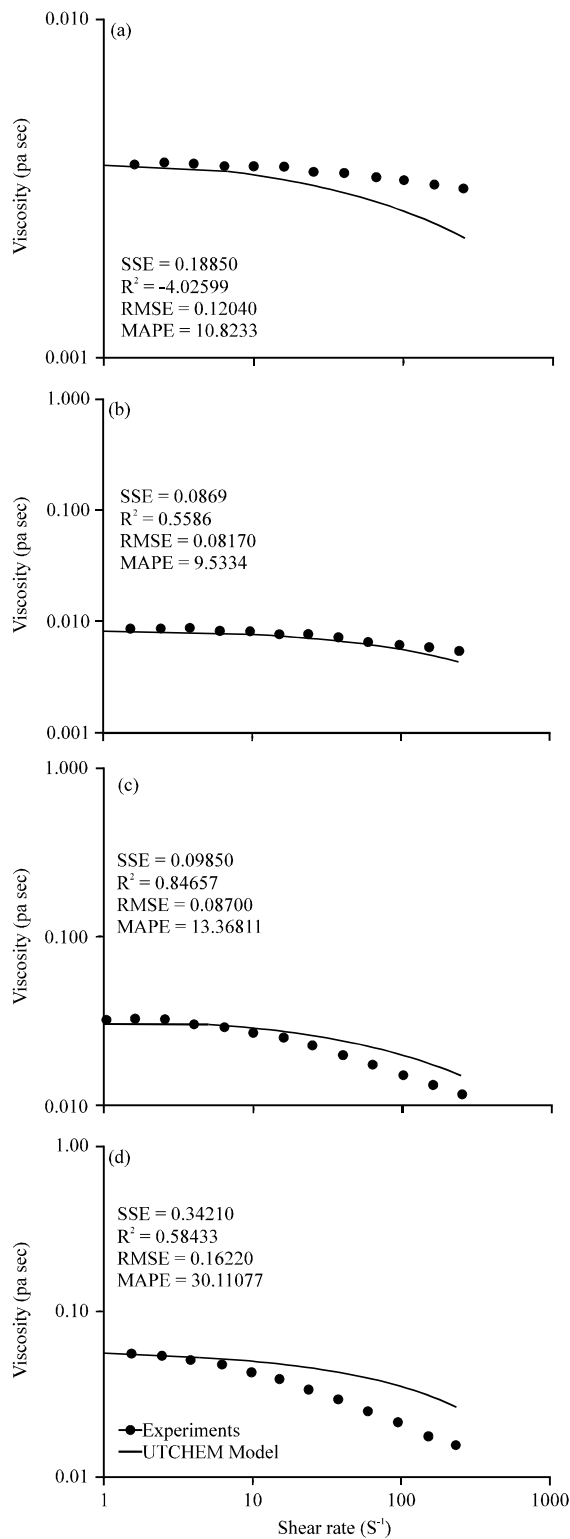


Fig. 5: Experimental data versus Meter's model prediction for a salinity of 10 g/L NaCl and polymer concentration of: a) 1000 ppm; b) 2000 ppm; c) 4000 ppm and d) 5000 ppm

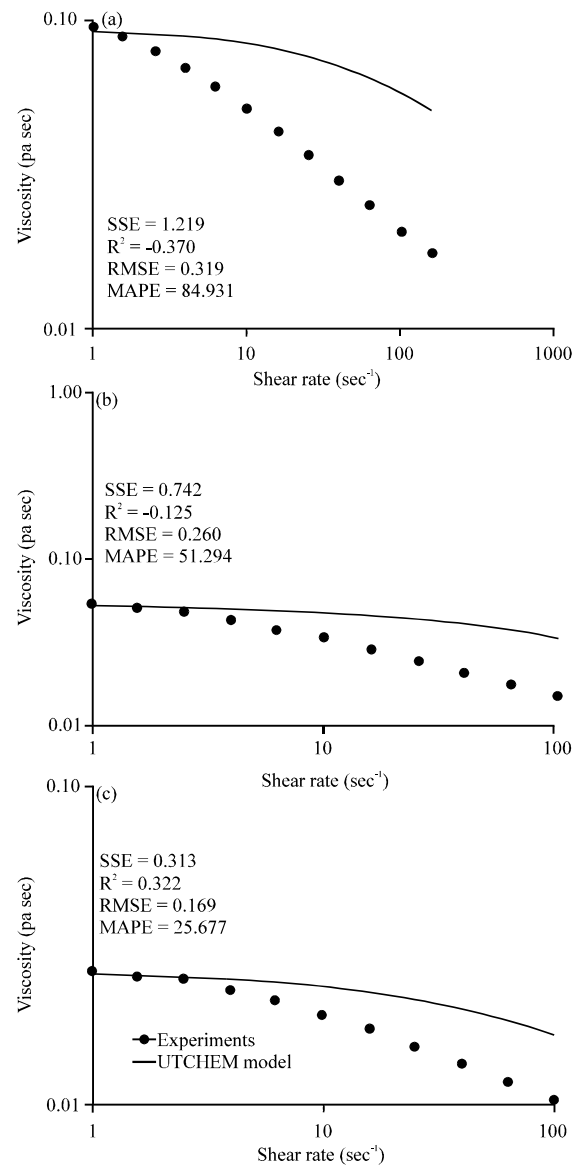


Fig. 6: Numerical predictions with the viscosity Model against experimental data for polymer solution of 5 g/L NaCl and polymer concentration of: a) 5000 ppm; b) 4000 ppm and c) 3000 ppm

prediction generated considerable error values, for example MAPE's value for 3000, 4000 and 5000 ppm polymer concentration in 5 wt.% NaCl were computed to be 25.67, 51.3 and 84.931, respectively. Perhaps, the model is not capable to take into account salinity effects. This shortcoming may be due to the simplifying assumptions (One-Factor-at-A-Time, OFAT method) used in developing the model and finding fitting parameters.

Polymer solution viscosity is a function of different variables and when a process contains two or more

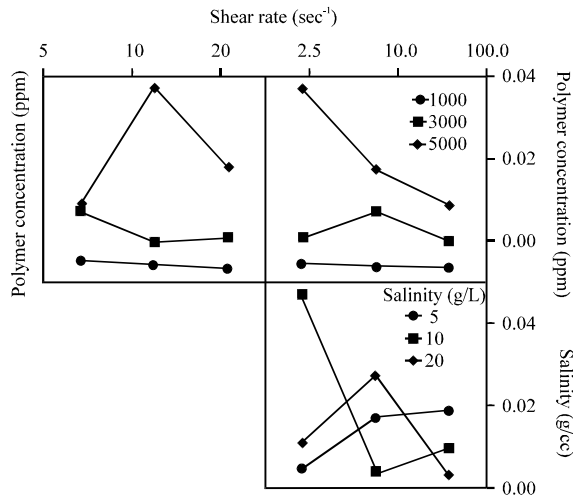


Fig. 7: Interaction plot for viscosity (data means)

variables, there exists the possibility of variable-to-variable interaction. An interaction exists between variables when the effect of one variable on the response depends on the level of another variable (Babu *et al.*, 2014). Two-factor interactions between variables can often be identified by simple graphs of the experimental response plotted as a function of the two involved variables. Figure 7 shows the plots variable-to-variable interaction for polymer concentration, salinity and shear rate used in this research. These plots show the response plotted as a function of one of the variables with the levels of the other variable distinguished by different types of lines.

Generally, when the lines in an interaction plot are parallel there is no interaction between the variables divergent lines is an indication of interaction between the variables. Figure 7 suggests that there are significant interactions between the variables. OFAT method ignores the interactions and so it fails in certain cases when the effects of those interactions are relatively large.

Design Of Experiments (DOE), a formal structured technique can be considered as an alternative to OFAT. The interactions management between variables is a weakness of the OFAT method and a strength of DOE method (Xu *et al.*, 2013). Any situation that involves a response that varies as a function of one or more independent variables can be studied by DOE. DOE is specifically designed to address complex problems where more than one variable may affect a response and two or more variables may interact with each other. Beside an inefficient use of resources, OFAT is not capable for detecting the presence of or quantifying the interactions

between variables which is a normal practice for DOE. Therefore, using DOE instead of OFAT in developing such model as this will lead to more accurate prediction of polymer solution viscosity.

CONCLUSION

UTCHEM simulator procedure has been selected to Model viscosity property of bulk polymer solution. Model output evaluation showed accurate prediction ability for zero shear rate viscosity but inaccurate for polymer solution at increased shear rate. Inaccuracy of One-Factor-at-A-Time (OFAT) approach in modeling polymer solution viscosity may be due to ignoring the existing interaction between process variables or parameters. An accurate approach in dealing with several factors is an experimental strategy in which factors are varied together, instead of one at a time. Design Of Experiments (DOE) gives the answers that we seek with a minimum expenditure of time and resources. DOE method is capable of detecting the presence of or quantifying the interactions between variables.

SUGGESTIONS

Further, research will be to experimentally study DOE method and then use the results for the formulation of a new constitutive equation and then use the results for the formulation of a new cons.

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