

# Rheological Studies on Interactions between CTAB and PEG in an Aqueous Solution Using RSM

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**ABSTRACT:** *In this work, the study of the rheological behavior of the aqueous solution of cationic surfactant, cetyltrimethylammonium bromide (CTAB) and nonionic polymer, polyethylene glycol (PEG 3000) has been carried out. Response surface methodology of design of experiment technique was adopted to identify the effect of different variables and their interactions on viscosity. A preliminary experimental investigation was carried out to evaluate the rheological behavior of aqueous PEG, aqueous CTAB, and also of the binary solution of them. It is found that they all show Newtonian behavior for a shear rate of up to  $1000\text{ s}^{-1}$  for the studied concentrations. For the shear rate above  $1000\text{ s}^{-1}$  aqueous PEG solution shows shear thickening behavior. Combinations of levels of variables i.e. [surfactant], [polymer], and temperature were determined using a face-centered central composite design (FCD) of response surface methodology. Through regression, a quadratic model was generated and found to be very accurate in describing the relation between response and parameters with  $R^2 = 0.987$ , predicted  $R^2 = 0.9412$  and adjusted  $R^2 = 0.9776$ . The effect of interaction between surfactant and polymer on dynamic viscosity is identified with the help of contour and response surface plots. A sudden increase in viscosity is observed at low CTAB concentrations which were the result of weak interactions between CTAB and PEG and the effect of these interactions is found to be more pronounced at high temperatures.*

**KEYWORDS:** *Surfactant; Nonionic polymer; Rheology; Viscosity; Shear rate; Temperature.*

## INTRODUCTION

A variety of surfactants and polymers are used in many industries such as oil drilling, enhanced oil recovery, cosmetics, pharmaceutical formulations, food products, household and industrial detergents, paints, and coatings among others. Polymer-surfactant mixtures are used in extensive commercial applications and their behavior, both in bulk and at interfaces is relevant. When present together in a solution they interact with each other to

form polymer-surfactant aggregates due to which superior characteristics in the system can be achieved. These interactions can be the result of the electrostatic or hydrophobic forces between surfactant and polymer [1-4]. It is evident, by a lot of research work carried out on individual surfactants, polymers, and mixed polymer-surfactant mixtures from the last few decades, that the solution of certain polymers and surfactants

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can exhibit molecular interactions that may affect the rheological and physicochemical properties of the solutions. These mixtures can be either weakly interacting mixtures or strongly interacting mixtures. The nature of these interactions depends on the polymers and surfactant's electrical charges, structural conformation, hydrophobicity of the polymer, non-polar tail of the surfactant, temperature, and the presence of other additives. Interactions between surfactants and ionic polymers have been studied extensively as compared to the system containing nonionic polymers and surfactants. Among the ionic surfactants, anionic surfactants are found to be more interacting with nonionic polymers as compared to cationic surfactants. The electrostatic forces are relatively weak in neutral polymer-cationic surfactant systems and generally interactions are due to the hydrophobic forces. Interactions are also favored by the relative bulkiness of the cationic headgroup [5-10]. The balance between the hydrophilic and hydrophobic polymer segments determine the solubility of the polymer in water. In the same way, the aggregation of surfactants in aqueous solution is controlled by the complex balance of amphiphilic moieties and ionic interaction [11].

These interactions can be studied qualitatively through the study of rheological and physicochemical properties of the system. When surfactant polymer form association structures, chain mobility in polymer solution decreases due to the network formation and entanglement brought about by the surfactant micelles and hence viscosity is increased. Even larger increases in viscosity can be observed in oppositely charged polymer-surfactant systems or even gel formation due to the increased chain entanglement resulting from the cross-linking of bound surfactant clusters [12-17]. In the case of cationic surfactant and nonionic polymer system interactions are rather weak and identifying the effect of these interactions on viscosity is a relatively difficult task and requires very precise measurements at very close intervals of variables. When considering the effect of three or more factors, the One Factor At A Time (OFAT) technique will require a huge amount of data and also, it is quite ineffective in determining whether the independent factors are interacting with each other or not. In order to elucidate these drawbacks Response Surface Methodology (RSM) is proposed. A statistical approach of RSM has recently been applied

to investigate these interactions. RSM is a multivariate statistical tool that offers a new approach to investigate the relationship between factors and response. RSM provides better results, reproducibility, and process optimization with a fine perspective for predictive model development [18-20]. In RSM, 3-D graphical representation is used to describe the collaborative effects of process variables and their subsequent effects on response. Face-centered Central Composite Design (FCD) is a factorial design, used to assess the quadratic response surface and for developing second-order polynomial models in RSM. It consists of a set of factorial points and the replicates of the center point which helps in mitigating the pure error.

In the present investigation, rheological analysis was used to study the interactions between cationic surfactant, cetyltrimethylammonium bromide CTAB and nonionic polymer, polyethylene glycol (PEG 3000). Manna and Panda [21] studied the behavior of PEG and CTAB in aqueous media and found that the viscosity of CTAB micelles in aqueous-PEG mixtures increase with PEG concentration and molar mass. Chauhan *et al.* [22] also studied the CTAB-PEG aqueous system through viscometric analysis and found similar results and concluded that there are some interactions between CTAB and PEG. Sardar *et al.* [23] studied the CTAB-PEG system using the conductivity, steady-state fluorescence, viscosity, and TEM techniques and identified the weak interactions between them. Behnoosh *et al.* [24] studied the aggregation behavior in mixtures of cetyltrimethylammonium bromide (CTAB), sodiumdodecylsulfate (SDS), and polyethylene glycol (PEG) in anionic- and cationic-rich by tensiometry, conductometry and cyclic voltammetry (CV). The size of particles and the inter-micellar interaction parameter in SDS/CTAB/PEG system were studied by CV. CV measurements show that the number of micelles decreased since the inter-micellar interaction coefficient ( $k_d$ ) decreased with an increase in polymer concentration and enhanced binding of surfactant monomers to the PEG. Amalia and Ramon [25] prepared DNA-based particles using CTAB (Cetyltrimethylammonium bromide) as the cationic surfactant and modified using two different additives: (Multi-Walled Carbon Nanotubes) MWNT

or PEG (Poly Ethylene Glycol). The use of both additives to form composites increased the stability of the gel particles. *Ali et al.* [26] studied the interaction of ionic surfactants such as sodium dodecylsulfate (SDS) and cetyltrimethylammonium ammonium bromide (CTAB) by using surface tension and conductivity measurements in the presence and absence of water-soluble polymer PEG. Surface tension study shows that PEG is surface active and its mixture with CTAB and SDS affects the CMC of these surfactants. CMC of CTAB increases with the addition of PEG and changes more when concentration or molar mass increases while the effect is opposite for SDS. A statistical approach to the design of the experiment is used in planning the experiments. Dynamic viscosity as response and [CTAB], [PEG], and temperature as independent variables were used in the models. A face-centered design (FCD,  $\alpha=1$ ) which is a type of central composite design with an axial point located at the center of each face of the design space is used for assessing the impact of process parameters on the response. A quadratic model is generated through regression. Contour plots and 3D response surface plots were generated to study the effect of interactions between CTAB and PEG on viscosity.

## EXPERIMENTAL SECTION

### Materials

The conventional cationic surfactant, cetyltrimethylammonium bromide CTAB ( $\geq 99.0\%$ , Merck, Germany), and nonionic polymer, Polyethylene glycol (PEG 3000, Fluka, Germany) were used without further purification. The molecular structures of CTAB and PEG are shown in Fig. 1.

### Preparation of the Solutions

Stock solution of CTAB with concentration of 40 mmol/L was prepared. The amount of CTAB to be added in the solution was calculated by using equation (1). Stock solution of PEG with concentration of 2 wt.% was prepared. The amount of PEG to be added in the solution was calculated with equation (2) which gives concentration in percent weight by volume basis. Ultrapure water produced by PURELAB Flex 3 which has the resistivity of 18.2 M $\Omega$ .cm at 298 K was used in preparation of all the solutions. Both the solutions were made homogeneous by stirring for around 20 minutes with the help of magnetic stirrer. The solutions were then stored undisturbed for

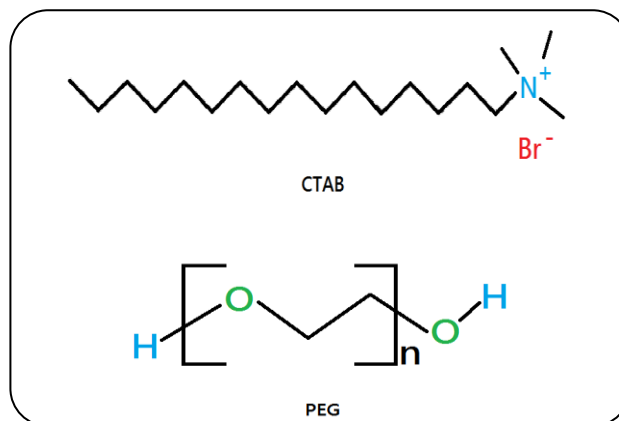


Fig. 1: Molecular structures of CTAB and PEG.

24 h at room temperature. The concentrated stock solutions were then diluted further to prepare solutions of different lower concentrations. The binary solutions were prepared by mixing appropriate amount of the stock solutions of surfactant and polymer.

Special care was taken in cleaning the glassware for the preparation of solutions. Before use, the glassware was cleaned by rinsing with double distilled water followed by cleaning it with chromic acid and then by rinsing again with double distilled water. Further, they were dried in an oven for the removal of moisture. The samples were allowed to stabilize before every measurement and made sure that bubbles were not present in the sample.

$$\text{Wt. (g)} = \text{Molecular Weight} \left( \frac{\text{g}}{\text{mol}} \right) \times \quad (1)$$

$$\text{Volume (ml)} \times \text{Molarity} \left( \frac{\text{mmol}}{\text{l}} \right) \times 10^{-6}$$

$$\frac{\% \text{wt.}}{v} = \frac{\text{mass of solute (g)}}{100 \text{ ml of solution}} \quad (2)$$

### Rheological Measurements

The viscosity ( $\eta$ ) of the different solutions were measured by using modular compact rheometer (MCR 102, Anton Paar Germany) fitted with a temperature control system (accuracy =  $\pm 0.01^\circ\text{C}$ ).

Cone plate geometry CP40-1 (diameter of 40 mm & cone angle of  $1^\circ$ ) is used for the measurements, as this system is easy to clean and requires a small sample volume because it has a default measuring position of 0.08 mm. Cone plate system is well suited for testing samples of low viscosity and viscoelastic liquids and have almost zero temperature gradient across the sample because of very small gap. The main advantage of using cone plates

measuring system comes from the fact that the produced shear rate is practically constant across the sample as it is independent of the radius of the plate. Eq. (3) shows the relation between shear rate and cone angle for the cone plate system. Thus, it is suitable for the measurements of Newtonian and as well as non-Newtonian liquids [27]. MCR 102 is also equipped with an air bearing which provides frictionless motion and the ability to measure normal force which helps in determining normal stress distribution in the sample.

$$\dot{\gamma} = \frac{\Omega}{\theta_0} \quad (3)$$

Where  $\dot{\gamma}$  is shear rate ( $\text{s}^{-1}$ ),  $\Omega$  is angular velocity ( $\text{rad/s}$ ), and  $\theta_0$  is cone angle ( $\text{rad}$ ). Before performing a measurement on sample inertia measurement of measuring system and motor adjustment were performed with the default settings of the rheometer. The rheometer is then calibrated by measuring the viscosity of ultrapure water. Both plates were cleaned with acetone before and after every measurement. For a measurement, 2-3 drops of the sample were placed on the bottom plate, then the measuring system was lowered the excess sample was trimmed and then the geometry moved to the measuring position. The viscosity of the samples was measured under stepwise linearly varying shear rates ( $\dot{\gamma} = 1 \text{ s}^{-1}$  to  $1000 \text{ s}^{-1}$ ) at 100 distinct points. An average was taken of these 100 points to obtain an accurate constant viscosity value. The measurements were carried out at temperatures of 298 K, 308 K, and 318 K. The sample was left on the bottom plate for a few seconds so that the sample achieved uniform desired temperature. For each measurement, viscosity was measured twice to minimize the experimental error. Further, the viscosity data obtained from the rheometer was used in Minitab software for analysis.

#### **Experimental design using response surface methodology**

Face centered central composite design (FCD,  $\alpha=1$ ) of response surface methodology was used to design the experiments. Variables considered are surfactant concentration, polymer concentration, and temperature. A design matrix was created in Minitab 18 by taking three levels of variables of all three factors. This design matrix contains 20 runs of various areas of variation factors and six replicates of the center point to minimize pure error.

The model was generated using regression analysis with the collected response variable data. Method of

Least Square (MLS) is a standard approach in regression technique used to fit a mathematical model to a set of experimental data generating the lowest residual possible. In the MLS, it is assumed that errors present a random distribution profile with a zero mean and a common unknown variance and that these errors are independent of each other. Equation (4) represents the standard format for fitted quadratic regression model [28].

$$Y_i = b_0 + \sum_{i=1}^k b_i X_i + \sum_{i=1}^k b_{ii} X_i^2 + \sum_{i < j}^k \sum b_{ij} X_i X_j \quad (4)$$

Where  $Y_i$  is the predicted response, subscripts  $i$  and  $j$  take values from 1 to  $k$  of the number of factors,  $b_0$  is a constant,  $b_i$ 's are the linear coefficients,  $b_{ii}$ 's are the quadratic coefficients,  $b_{ij}$ 's are the cross-product coefficients, and  $X_i$  and  $X_j$  are values of the investigated variables.

## **RESULTS AND DISCUSSION**

A preliminary experimental investigation was carried out to evaluate the rheological behavior of aqueous PEG, aqueous CTAB and also their binary solutions. Fig. 2 shows the viscosity versus shear rate of solution at different concentration of CTAB in water and it is found that CTAB solution shows Newtonian behavior. *Kuperkar et al.* [29] also reported Newtonian behavior of CTAB aqueous solution up to  $100 \text{ s}^{-1}$  shear rate. The viscosity of solution increased around 10 percent on addition of 10 mM CTAB in water. Fig. 3 shows plot of viscosity of 2 wt.% PEG solution at varying shear rate and it can be seen from the graphs that PEG solution has a constant viscosity for up to  $1000 \text{ s}^{-1}$  shear rate. Fig. 4 shows shear stress generation and viscosity of 2 wt.% PEG solution up to very high shear rate and it is observed that beyond  $1000 \text{ s}^{-1}$  shear rate, PEG shows shear thickening behavior. This is due to the increase in chain entanglement caused by high shear rate. *Brikov et al.* [30] also reported the similar behavior for PEG 4000. Fig. 5 shows the variation of viscosity as a function of CTAB concentration for 0.25 wt.% PEG solution at constant temperature of 308 K. Fig. 6 shows plot of shear stress versus shear rate of binary solution of CTAB and PEG and it can be seen that their binary solution also shows Newtonian behavior.

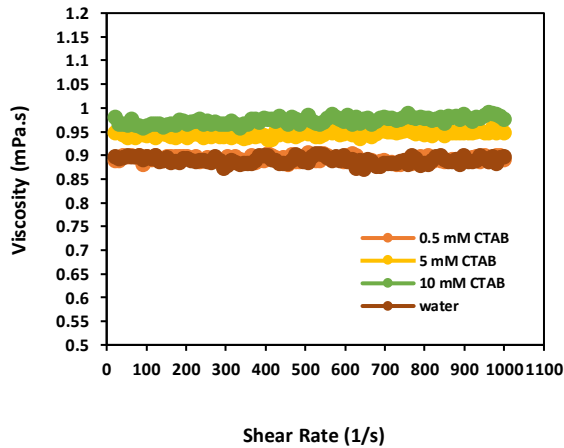


Fig. 2: Plots of viscosity versus shear rate at 298 K for different CTAB concentrations.

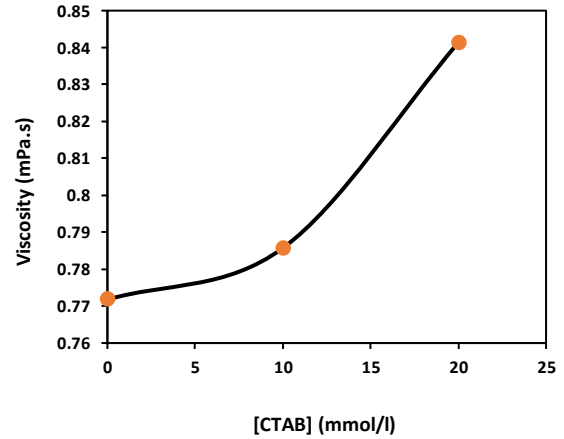


Fig. 5: Plots of viscosity versus surfactant concentration in the presence of 0.25 wt.% PEG at 308 K.

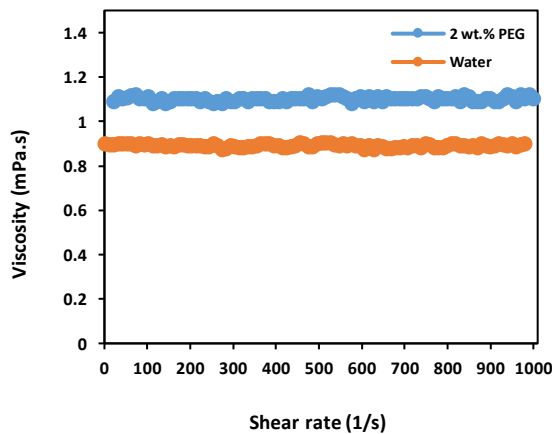


Fig. 3: Plots of viscosity versus shear rate at 298 K for 2 wt.% PEG solution.

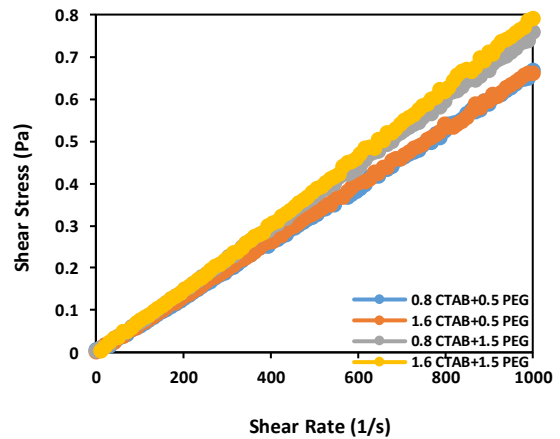


Fig. 6: Plots of shear stress versus the shear rate at 318 K for the binary solution of CTAB and PEG.

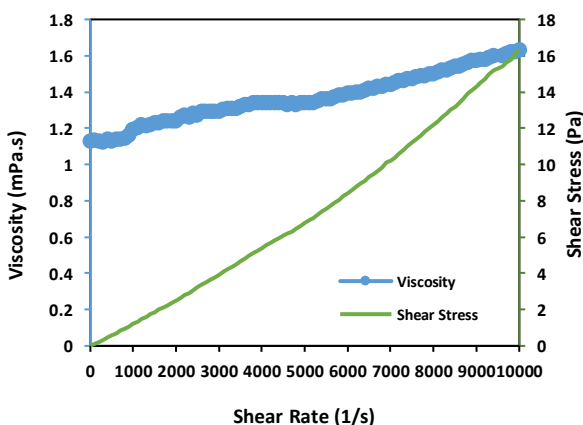


Fig. 4: Plots of viscosity and shear stress versus shear rate at 298 K for 2 wt.% PEG solution.

### Data analysis, modeling, and response surface methodology

A Face-Centered Design (FCD) is generated for viscosity as response and [CTAB], [PEG], and temperature as independent variables with three levels each as shown in Table 1. Measurements were conducted according to the order and combination of levels listed in Table 2.

### Model determination

A linear model is first generated using regression analysis with the collected response variable data which resulted in a significant lack of fit and the coefficient of determination ( $R^2$ ) less than 70%. The linear model failed to describe the relation between factors and response accurately, hence the linear model was discarded.

**Table 1: Coded variables and their corresponding uncoded values.**

Independent variables	Coded values and the corresponding values of parameters		
	-1	0	1
[PEG] (wt.%)	0	0.25	0.5
[CTAB] (mmol/l)	0	10	20
Temperature (K)	298	308	318

**Table 2: Standard run order generated with Minitab 18 using RSM/FCD in uncoded units.**

Run Order	Concentration of PEG (X1) (wt.%)	Concentration of CTAB (X2) (mmol/l)	Temperature (X3) (K)	Response	
				Viscosity (mPa.s)	
				Measured	Predicted
1	0.00	0	298	0.89666	0.887697
2	0.50	0	298	0.94929	0.95191
3	0.00	20	298	0.95154	0.960482
4	0.50	20	298	1.07000	1.061544
5	0.00	0	318	0.65221	0.6612
6	0.50	0	318	0.67292	0.664507
7	0.00	20	318	0.66552	0.663424
8	0.50	20	318	0.69408	0.70358
9	0.00	10	308	0.75526	0.741243
10	0.50	10	308	0.79583	0.793427
11	0.25	0	308	0.77177	0.777537
12	0.25	20	308	0.84136	0.833466
13	0.25	10	298	0.92138	0.927241
14	0.25	10	318	0.64299	0.635011
15	0.25	10	308	0.77089	0.767335
16	0.25	10	308	0.75089	0.767335
17	0.25	10	308	0.78573	0.767335
18	0.25	10	308	0.79014	0.767335
19	0.25	10	308	0.73693	0.767335
20	0.25	10	308	0.75089	0.767335

The experimental data were then fitted to the second-order polynomial Eq. (4). The backward elimination method was used to simplify the model and to obtain a model of adequate accuracy. ANOVA results of the quadratic model in Table 3 revealed that the model equation derived by regression could adequately be used to describe the relation of surfactant concentration, polymer

concentration, and temperature with viscosity. The model resulted in an F-value of 104.5 and an extremely low P-value (<0.0001) for viscosity implying that the model was highly significant and accurate. The P-value was used as a tool to check the significance of each of the term. The smaller the magnitude of P, the more significant was the corresponding term.

Table 3: Analysis of variance (ANOVA) for the response surface quadratic model.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	8	0.244541	0.030568	104.50	<0.0001
Linear	3	0.228125	0.076042	259.96	<0.0001
X <sub>1</sub>	1	0.006808	0.006808	23.27	0.001
X <sub>2</sub>	1	0.007820	0.007820	26.73	<0.0001
X <sub>3</sub>	1	0.213497	0.213497	729.88	<0.0001
Square	2	0.011393	0.005696	19.47	<0.0001
X <sub>2</sub> * X <sub>2</sub>	1	0.004661	0.004661	15.94	0.002
X <sub>3</sub> * X <sub>3</sub>	1	0.000609	0.000609	2.08	0.177
2-Way Interaction	3	0.005023	0.001674	5.72	0.013
X <sub>1</sub> * X <sub>2</sub>	1	0.000679	0.000679	2.32	0.156
X <sub>1</sub> * X <sub>3</sub>	1	0.001855	0.001855	6.34	0.029
X <sub>2</sub> * X <sub>3</sub>	1	0.002489	0.002489	8.51	0.014
Error	11	0.003218	0.000293		
Lack-of-Fit	6	0.000938	0.000156	0.34	0.888
Pure Error	5	0.002280	0.000456		
Total	19	0.247759			

Abb.: DF-Degree of freedom; SS-Sum of squares; MS-Mean square; F-Fisher test; P-Probability.

S=0.0171029, R<sup>2</sup> = 0.987, R<sup>2</sup> (adjusted) =0.9776, and R<sup>2</sup> (predicted) =0.9412.

Regression equation in uncoded units.

$$Y = 17.33 + 1.943X_1 + 0.0486X_2 - 0.0963X_3 + 0.000382X_2^2 + 0.000138X_3^2 + 0.00368X_1X_2 - 0.00609X_1X_3 - 0.000176X_2X_3 \quad (5)$$

Where  $Y$  is viscosity (mPa.s),  $X_1$  is PEG concentration (wt.%),  $X_2$  is CTAB concentration (mmol/l) and  $X_3$  is temperature (K). The model had an insignificant lack of fit (P-value =0.888) which means the regression model adequately describes the functional relationship between the experimental factors and the response variable. The coefficient of determination R<sup>2</sup> was 0.987 which implies that the data fits the model very well, the standard error was found to be adequately small (S=0.0171), S is measured in the units of the response variable and represents the variation of how far the predicted values fall from the experimental values. Model acceptability was also checked by analyzing the residual plot for viscosity (Fig. 7). The normal probability plot demonstrates that residuals are distributed near the straight line, which

indicates that actual values are very close to the predicted values (R<sup>2</sup> predicted = 0.9412). Also, the residuals are not having any obvious patterns (i.e., structure less), therefore the residuals are independent of one another [30,31].

The coefficient of the effect of factors and their interactions are shown in Table 4. Pareto chart (Fig. 8) illustrates the order of significant effect of the variables and their interaction affecting viscosity. It displays the absolute value of the standardized effects of factors and draws a reference line on the chart. Any effect that extends past this reference line is potentially important. The most noticeable effects on the viscosity were exerted by temperature (P-value <0.0001) as can be seen in Pareto chart, followed by CTAB concentration (P-value <0.0001) and PEG concentration (P-value =0.001), Coefficient for temperature is negative which is obvious because temperature has inverse effect on viscosity. PEG and CTAB has a positive effect on viscosity and effect of CTAB is larger than PEG because of very low range of PEG concentration and high range of CTAB concentration is used in the study [32].

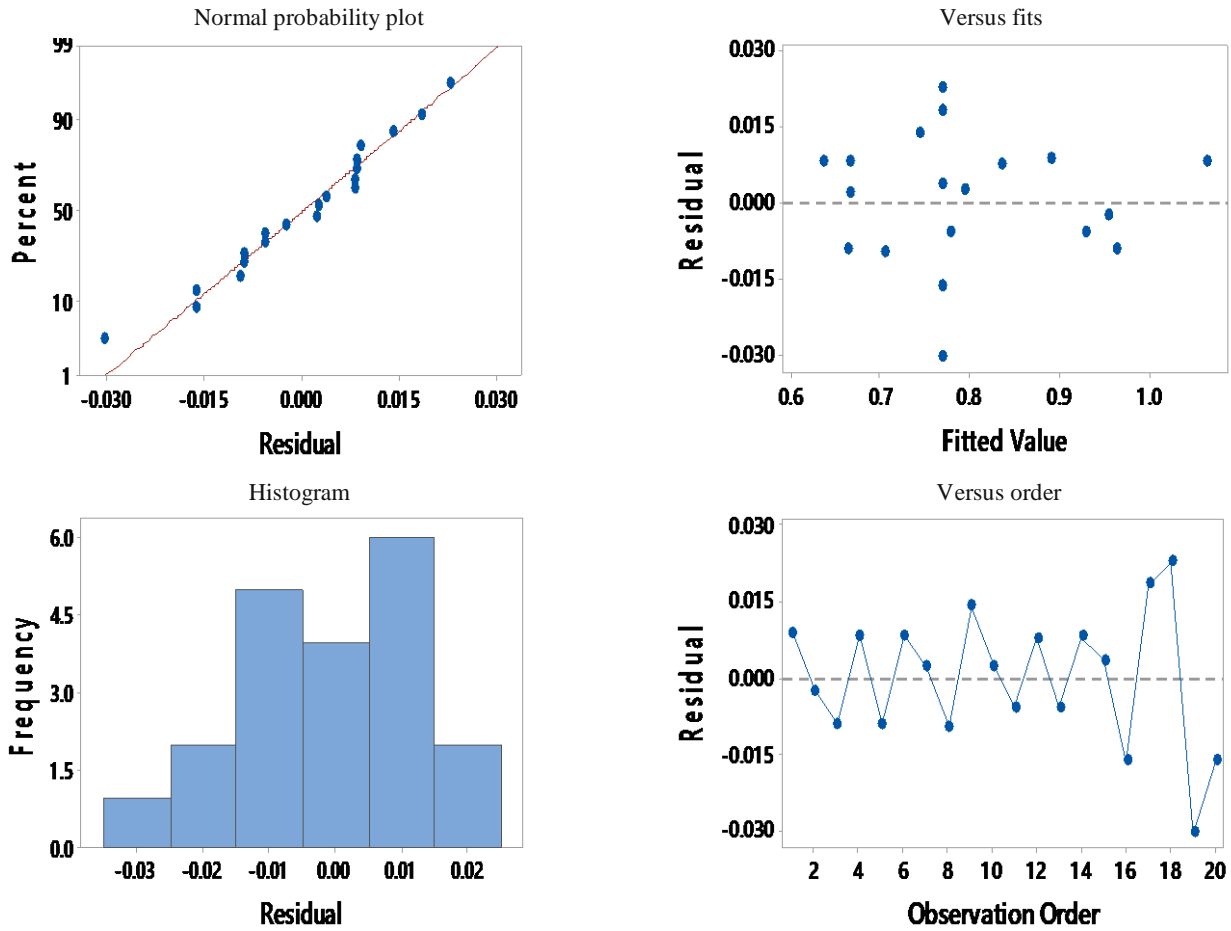


Fig. 7: Residual plots for viscosity.

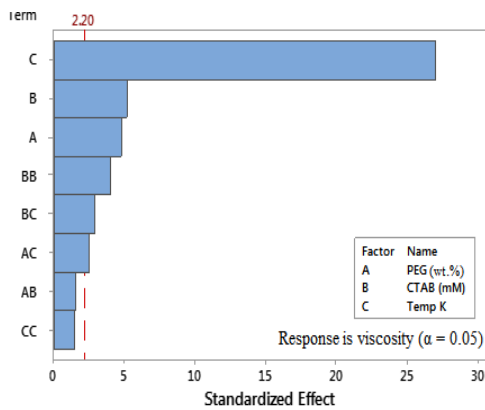


Fig. 8: Pareto Chart of the Standardized Effects.

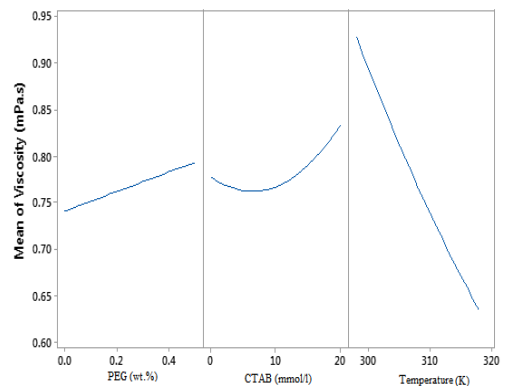


Fig. 9: Plots of individual effects of variables on viscosity.

Individual effect of [PEG], [CTAB] and temperature on viscosity is shown in Fig. 9. It can be seen that the effect of temperature is more pronounced as compared to the effect of other two factors which attributed to the two reasons first increment in the chain mobility due to the

increase in temperature and second is that increase in temperature hinders the micelle formation of CTAB due to thermal agitation and increased electrostatic repulsion between the ionic head group which results in higher CMC at high temperature [29]. Fig. 10 shows plot of interaction



Table 4: Table of coded coefficients of significant terms.

Term	Coefficient	Standard Error Coefficient	P-Value (Probability)	Variance inflation factors (VIF)
Constant	0.76733	0.00574	0.000	
X <sub>1</sub>	0.02609	0.00541	0.001	1.00
X <sub>2</sub>	0.02796	0.00541	0.000	1.00
X <sub>3</sub>	-0.14612	0.00541	0.000	1.00
X <sub>2</sub> * X <sub>2</sub>	0.03817	0.00956	0.002	1.56
X <sub>3</sub> * X <sub>3</sub>	0.01379	0.00956	0.177	1.56
X <sub>1</sub> * X <sub>2</sub>	0.00921	0.00605	0.156	1.00
X <sub>1</sub> * X <sub>3</sub>	-0.01523	0.00605	0.029	1.00
X <sub>2</sub> * X <sub>3</sub>	-0.01764	0.00605	0.014	1.00

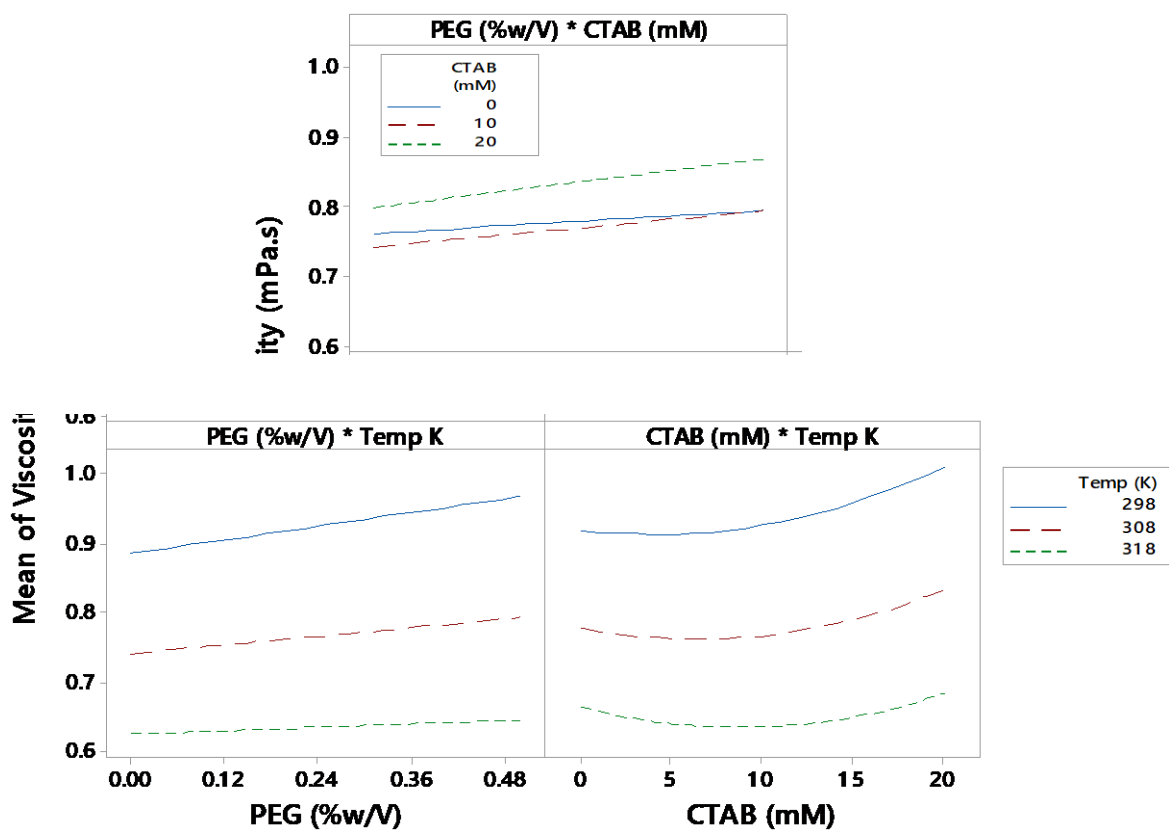


Fig. 10: Plots showing the interaction between variables.

between variables. It can be seen that there is no significant interaction between CTAB and PEG (also can be seen from Table 4, for X<sub>1</sub>\* X<sub>2</sub>, P >0.05). However, the interaction of temperature with CTAB and PEG is present (P<0.05) and at low temperature these interactions are slightly more synergistic than at higher temperature [33-34].

### Response Surface Analysis

The contour plots and three-dimensional surface plots (Fig. 11) are the graphical representations of equation (5). Each plot shows the simultaneous effect of temperature and [PEG] and temperature and [CTAB] on viscosity while the [CTAB] and [PEG] levels are fixed respectively. Almost horizontal contours also suggest that the effect

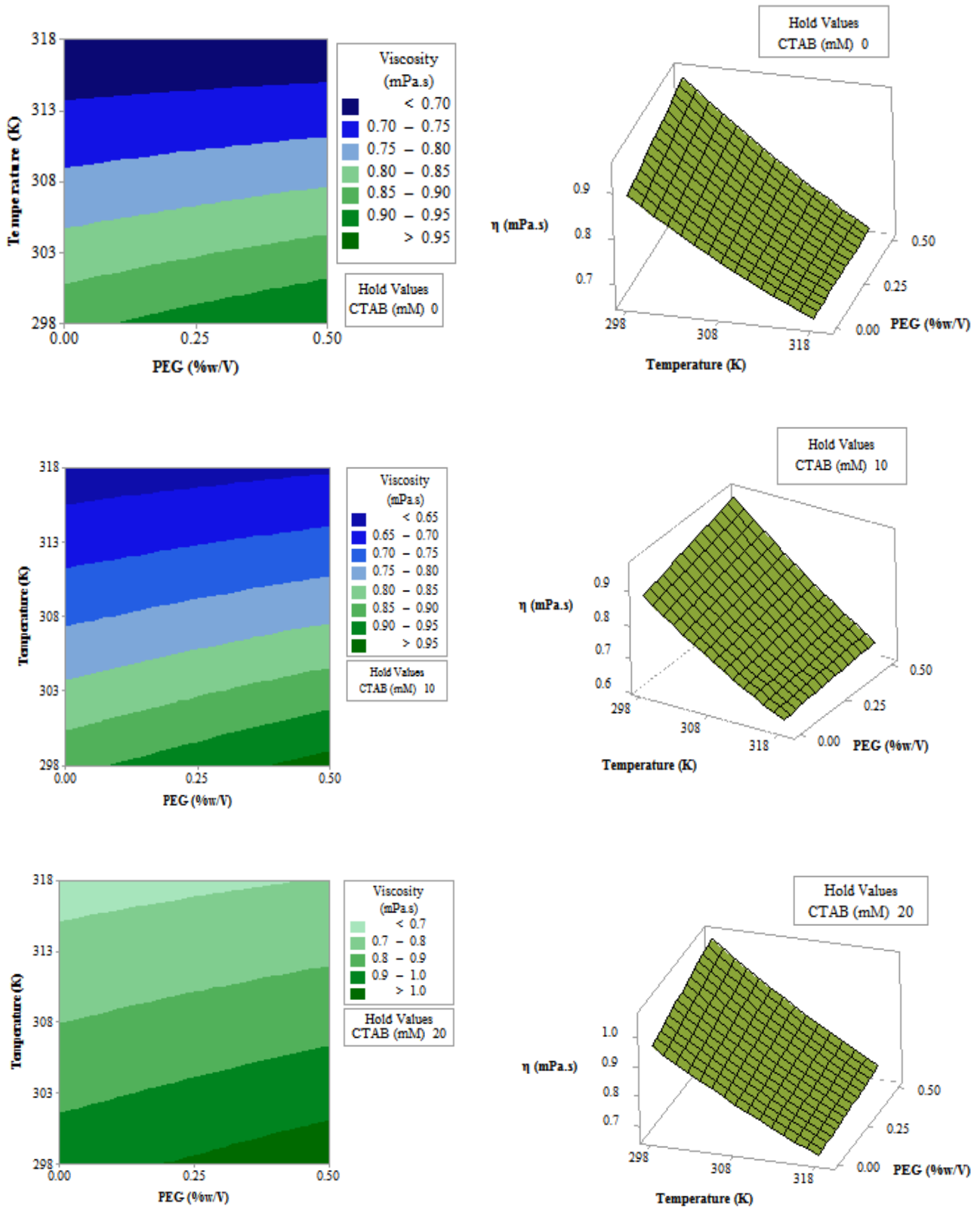


Fig.11: Contour and 3D surface plots showing effect of temperature on viscosity with respect to the [PEG] and [CTAB].

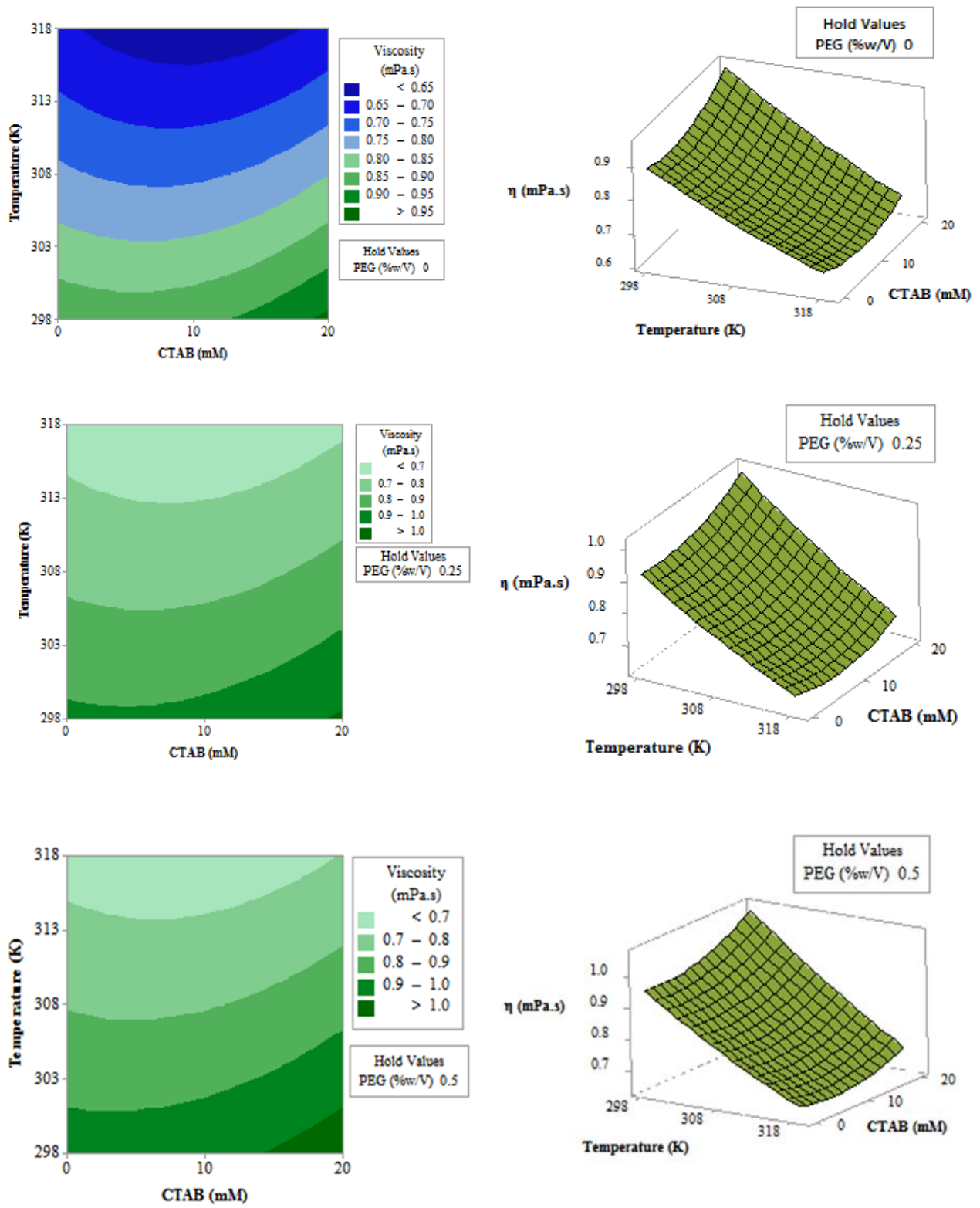


Fig. 11: Contour and 3D surface plots showing effect of temperature on viscosity with respect to the [PEG] and [CTAB]. (Continuation)

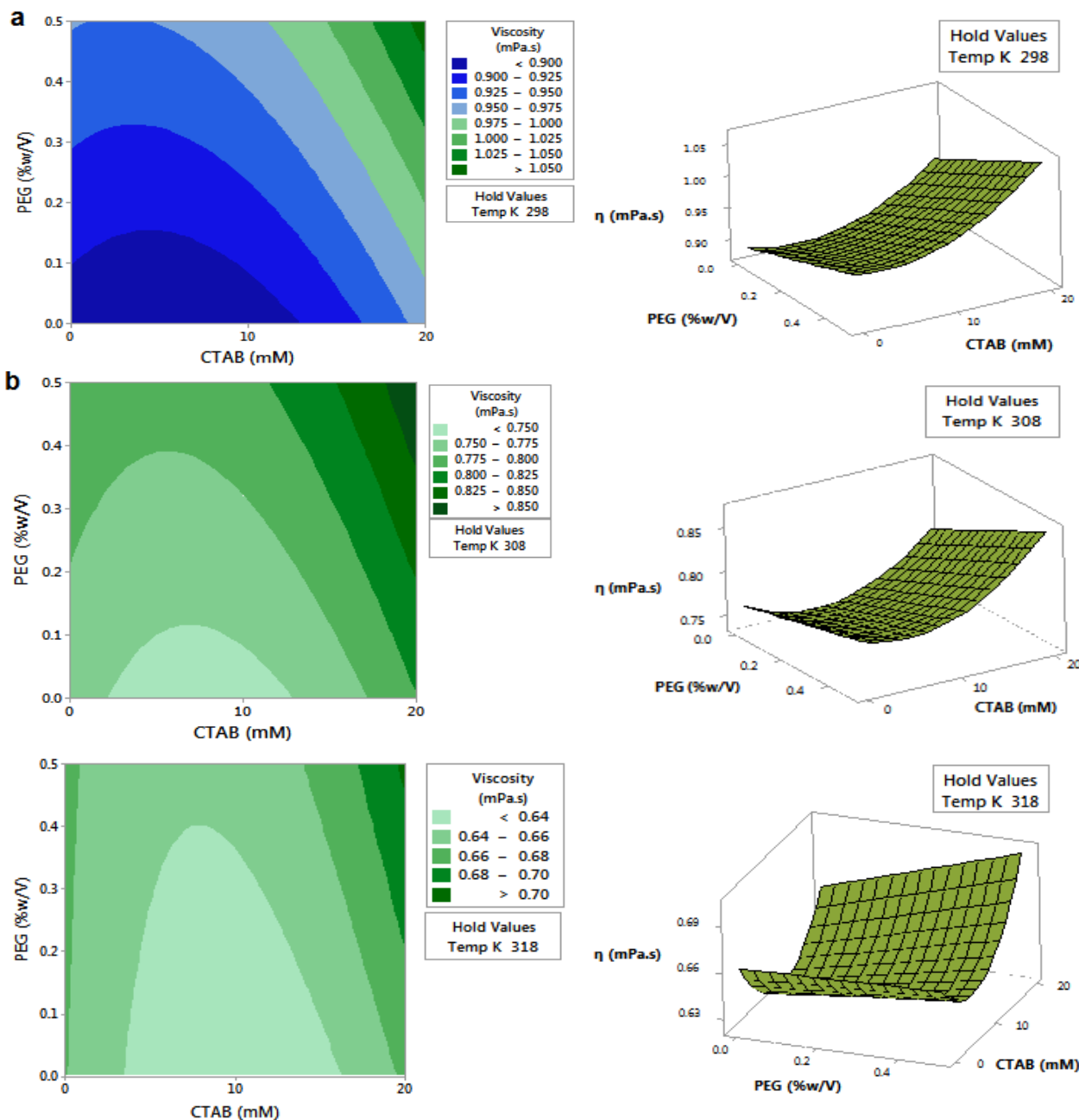


Fig. 12: Contour and 3D surface plots showing the effect of PEG and CTAB concentration on viscosity at (a) 298 K, (b) 308 K, and (c) 318 K.

of [PEG] and [CTAB] on viscosity is very weak as compared to the effect of temperature, and nearly flat surface plots for all concentrations of PEG suggest there is no unusual change in viscosity.

It is well documented that the interaction between a nonionic polymer such as PEG with an anionic surfactant can result in charging up the polymer and as result giving polyelectrolyte properties to the nonionic polymer. This effect reveals itself as a significant increase in viscosity at

a certain concentration near CAC/CMC of the surfactant, but in case of cationic surfactant interactions are relatively weak hence increase in viscosity is not tremendous [23]. The contour plots and three-dimensional surface plots (Fig. 12) which are also the graphical representations of equation (5). Each plot shows simultaneous effect of PEG and CTAB concentration on viscosity while the temperature levels are fixed. This three-dimensional visualization allowed the relationships between the

experimental levels of each factor and the response to be investigated to identify interactions between different factors. The viscosity of a polymer solution depends on the concentration and average molecular mass of the dissolved polymer. At higher polymer concentrations the polymer chains become more entangled with each other and chain mobility decreases, thus the viscosity increases with polymer concentration. From the contour and response surface plot (Fig. 12) individual effects of polymer concentration, surfactant concentration and the effect due to the interaction between them can be identified on viscosity. It can be seen from the surface plot, that the edge of the surface along the PEG (% wt/v) axis is almost horizontal and becomes almost parallel to the axis as the temperature is increased. On the other hand, if we move towards the opposite edge, the slope of the surface begins to increase with the CTAB concentration i.e., the increase in viscosity is relatively sharp in the presence of CTAB which suggests that there is interaction between macromolecule and micelles. However, a slight dip in viscosity is seen in Fig. 12 (c) at CTAB concentration equal to 10 mmol/l which could be the result of a slip that happened between the measuring system of the rheometer and sample [35].

## CONCLUSIONS

A rheological study of aqueous solutions of nonionic polymer (PEG 3000) and cationic surfactant CTAB is carried out to identify the interactions between surfactant and polymer with the help of Response Surface Methodology (RSM). Rheology of aqueous solution of CTAB up to 20 mmol/l is studied and it is found that CTAB aqueous solution shows Newtonian behavior for shear rate up to  $1000\text{ s}^{-1}$ . The aqueous solution of PEG 3000 also showed Newtonian behavior up to  $1000\text{ s}^{-1}$  shear rate and shear thickening behavior was observed beyond  $1000\text{ s}^{-1}$  shear rate. PEG-CTAB solution in water also shows Newtonian behavior at the studied surfactant and polymer concentration for up to  $1000\text{ s}^{-1}$  shear rate. Viscosity as the response and [CTAB], [PEG] and temperature as independent variables are used in RSM. Parameter levels were designed using Face-centered Central Composite Design (FCD) of RSM. Quadratic model was generated through regression and found to be very accurate in describing the relation between response and parameters, with coefficients of determination of  $R^2 = 0.987$  and  $R^2$  (adjusted) = 0.9776 with an insignificant lack of fit. The response is analyzed using contour and

surface plots. Results show that the increase in viscosity is relatively sharp in the presence of CTAB as compared to PEG concentrations alone, however the increase in viscosity is relatively small which suggest there are weak interactions between CTAB and PEG. Also, this effect becomes more clear at high temperature which could be the result of increased hydrophobicity at high temperature. RSM is found to be very efficient way for identifying these interactions between surfactant (CTAB) and polymer (PEG).

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