Application of Response Surface Methodology and Box—Behnken Design for the Optimization of the Stability of Fibrous Dispersion Used in Drilling and Completion Operations

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ABSTRACT: Fibers are extensively used as a fluid additive in the oil and gas industry to improve hole-cleaning performance, control fluid filtration loss, and enhance hydraulic fracturing effectiveness. Generally, a small amount of fiber is dispersed in the base fluid to achieve the desired results without increasing the viscosity of the base fluid. Nevertheless, sustaining a uniform fiber dispersion can be challenging under wellbore conditions, which is essential for fibers' functionality. Consequently, a better understanding of fiber suspension or stability in base fluids is necessary for their efficient utilization in drilling and completion operations. In this study, response surface methodology (RSM) and box—behnken design (BBD) are used to investigate the stability of fiber in polymeric base suspensions, including carboxy methyl cellulose (CMC), polyacrylamide (PAM), and xanthan gum (XG). The BBD of three factors was selected to observe the influence of polymer concentration, fiber concentration, and temperature on fibrous suspension stability, with three levels of design factors (low, mid, and high) and two fiber aspect ratios (3 and 12 mm fibers). The base fluid polymer concentration ranged from 1 to 8 vol %, fiber concentration ranged from 0.01 to 0.08 wt %, and the temperature was varied from 25 to 80 °C. The stability measurements were analyzed using Minitab, subsequently, evaluating the factors’ impact and interactions and determining the optimum conditions for the stability of the fibrous suspensions. The results predicted by the developed model were in good agreement with the experimental results $R^2 \geq 0.91−0.99$. The sensitivity analysis showed that base fluid polymer concentration is the most significant factor affecting fibrous suspension stability. At high polymer concentrations, fiber concentration and temperature effects are minimal, while the temperature effect on the stability was observed at low concentrations (e.g., low suspension viscosities). The fiber aspect ratio indirectly affects system stability. Long fibers have a better tendency to entangle and form a structured network, which in turn hinders the buoyancy that induces individual fiber migration. On the contrary, short fibers do not form a network, allowing them to easily migrate to the surface and agglomerate at the top layer (unstable region). Optimization results revealed that suspensions with viscosities above 50 mPa·s are sufficient to maintain the stability of the suspensions at ambient (25 °C) and elevated (80 °C) temperatures.

1. INTRODUCTION

Although significant advancements have been made in drilling and completion technologies, still cutting transport is a persisting problem in the oil and gas industry.¹ Inadequate hole cleaning increases the non-productive time (NPT) and reduces the rate of penetration (ROP), increase in drag and torque during tripping, excessive bit wear, fluid lost circulation, and stuck pipe.²⁻⁴ Drilling fluids and drilling sweeps are commonly used in the petroleum industry to enhance wellbore-cleaning performance throughout the drilling operations. Drilling fluids are classified according to their base fluid type into water-based muds (WBM) and oil-based muds (OBM).⁵⁻⁶ Water-based muds encounter instability problems in shale formations and extreme conditions of high temperature and high pressure. Although oil-based muds exhibit good
Table 1. Drilling Fluid Polymer Structure

| Name                          | Structure | Source                                      |
|-------------------------------|-----------|---------------------------------------------|
| Carboxy Methyl Cellulose Sodium (CMC) | ![CMC Structure](image) | Research lab fine chem industries, Mumbai, India |
| Non-ionic Polyacrylamide (PAM) | ![PAM Structure](image) | SNF, Andrezieux, France                     |
| Xanthan Gum (XG)              | ![XG Structure](image) | Arshine pharmaceutical co. ltd, Hunan, China |

**thermal stability compared to WBMs.**

Fibers are used in water-based drilling and completion formulations; they are utilized in various applications such as well-fracturing and hole-cleaning operations. Cutting transport (hole cleaning) depends on various parameters, including the viscosity and density of the drilling fluid, flow rate, wellbore geometry, inclination angle, annular velocity, and cutting shape, size, and weight. These parameters control the hole cleanout efficiency, affecting the drilling operational cost and time. Numerous studies have shown the effectiveness of fibrous drilling sweeps in horizontal and highly deviated wells. The addition of a small amount (concentrations less than 0.06 wt %) of flexible monofilament fiber into drilling fluids has minimal effect on their rheological properties.

Nevertheless, drilling fluids containing fibers with concentrations higher than 0.09% experience changes in rheological properties; the addition of 0.4% fiber into hydroxypropyl guar gel showed an increase in fluid viscosity by 3 orders of magnitude. With the increase in fiber concentration, the consistency index “K” increased and fluid-behavior index “n” decreased, indicating a more rigorous shear thinning behavior of the fibrous fluid.

An experimental investigation conducted on spherical glass bead particles revealed that the addition of a small amount (0.02–0.04%) of fiber to a 0.35% xanthan gum suspension reduced the particle settling velocity by approximately 50%.

The presence of fiber in drilling sweeps provides additional lifting capacity to remove cuttings that cannot be removed or lifted by conventional drilling fluids. In addition to the viscous drag of base suspension, the fiber drag aids the lifting of particles in the suspension by forming a stable fiber network. The fibrous suspension functionality is due to mechanical interactions between particles and the fiber network and hydrodynamic interactions between the suspension and particles. Pradhan et al. computation has shown that fiber particles disperse randomly within the fluid system under static conditions in fibrous fluids. Under dynamic conditions, a gradual increase in shear rate detangles some of the fiber networks and tends to orient fiber particles in the flow direction. Finally, an excessive increase in shear rate results in a parallel orientation of fiber particles in the fluid flow direction (majority of fibers are parallelly oriented). The main problem that complicates the use of fibrous fluids is the instability of the fiber network within the fluid medium. The stability of a fibrous fluid is defined as the ability of fiber particles to remain dispersed in the fluid for an extended time. Only a few studies have been performed to investigate the segregation behavior of fiber particles in drilling and completion fluids. For example, George et al. established a mechanistic model that describes the behavior of fibers in a multiphase complex fluid system with fluid rheological properties as the main modeling parameters. Fibers tend to orient horizontally while separating within the drilling fluid. High-density fluids require higher yield stress to prevent fibers from segregation. A low fluid behavior index “n” and high consistency index “K” are favorable for the stability of fibrous suspensions.

The implementation of computational fluid dynamic (CFD) and design of experiment (DOE) techniques have enabled the identification of dominating factors affecting a specific parameter (response) that is vital in field operations. Ensuring the stability of the fibrous fluid is the first step toward efficient cutting transportation and removal. Therefore, the aim of this study is to identify optimum conditions for fiber network stability in various base fluids, including suspensions of carboxymethyl cellulose (CMC), polyacrylamide (PAM), and...
xanthan gum (XG). Box–Behnken design (BBD) and response surface methodology (RSM) are employed to obtain statistical models for fiber stability optimization and identification of their stability regions. Factors including the polymer concentrations, fiber concentrations, fiber aspect ratio, and temperature are subjected to sensitivity analyses, highlighting their ascendency and interactional effect on the formulation stability.

2. MATERIALS AND METHODS

2.1. Materials. Virgin polypropylene monofilament synthetic fibers with a specific gravity of 0.91 and a melting point of around 163–177 °C were utilized with two aspect ratios (3 or 12.5 mm in length and 100 μm in diameter). Various polymeric water-based drilling fluids were prepared. Table 1 shows the structure of each base polymer. Details of the test matrix are illustrated in Table 2.

2.2. Experimental Procedure. Stability measurement that was obtained following a developed systematic procedure for all base fluids and fibers is as follows:

i. The required amount of the polymer (CMC, PAM, or XG) was weighted and added to deionized water in a 500 mL beaker. The gradual addition of polymer powder was carried out while mixing (IKA Model EUROSTAR 20) at 600 rpm for 30 min, followed by prolonged 3 h of mixing with multi-position hot plate stirrers (LABEC). The suspensions were left to hydrate for 24 h. Mixing speed was maintained high enough to avoid lump formation while avoiding excessive mixing that introduces air into the suspension.

ii. Following hydration, the polymeric suspension underwent 10 min of agitation to ensure homogeneity. Subsequently, fibers were added to 250 mL of the suspension while mixing at 450 rpm for 2 min. To ensure good dispersion, the clumps of fibers were separated manually using a spatula prior to the addition to the polymer suspension. Some fibers were dyed with red color to resolve the visibility problems associated with the XG polymer suspension.

iii. The fibrous suspensions were transferred immediately to 250 mL graduated cylinders and kept inside an oven at the required temperature for 1 h.

iv. Finally, the graduated cylinder was taken out of the oven and the stability of the suspension was measured in terms of dispersion volume. The dispersion volume is used to determine the stability of the sample. The calculation procedure of suspension stability is discussed in detail in the following section.

2.3. Stability Assessment Method. In this study, fiber stability within the formulation is assessed by measuring the amount of fibers remaining in the suspension. A stable fluid is capable of suspending fibers throughout its volume for an extended time (Figure 1a). In contrast, an unstable system is unable to retain fibers in the dispersed form for a long period, allowing the migration of fiber particles to the upper section of the suspension column (Figure 1b). The addition of the polymer in water reduces fiber migration. Therefore, a fiber suspension of pure water is used as a baseline reference for the assessment of fibrous fluid stability. Different fiber suspension samples were prepared as discussed above and left in an oven for 1 h under

| Table 2. Limits of the Studied Parameters |
|------------------------------------------|
| factor | symbol | low (−1) | central (0) | high (+1) |
| base fluid polymer concentration (vol %) | A | 1 | 4.5 | 8 |
| fiber (wt %) | B | 0.01 | 0.045 | 0.08 |
| temperature (°C) | C | 25 | 52.5 | 80 |

| Two lengths of fibers: 3 and 12.5 mm. |

| Table 3. Fiber Bed Formed in Water Using 3.00 mm-Long Fibers |
|---------------------------------------------------------------|
| fiber concentration (wt %) | reference bed volume (mL ± 0.02) |
| 25 °C | 52.5 °C | 80 °C |
| 0.02 | 5.0 | 2.5 | 2.0 |
| 0.04 | 6.5 | 5.0 | 4.0 |
| 0.05 | 7.0 | 5.8 | 5.0 |
| 0.06 | 7.2 | 6.5 | 6.0 |
| 0.08 | 10.0 | 7.5 | 6.4 |

| Table 4. Fiber Bed Formed in Water Using 12.5 mm-Long Fibers |
|---------------------------------------------------------------|
| fiber concentration (wt %) | reference bed volume (mL ± 0.02) |
| 25 °C | 52.5 °C | 80 °C |
| 0.02 | 40.0 | 16.0 | 12.0 |
| 0.04 | 65.0 | 23.0 | 16.5 |
| 0.05 | 68.5 | 29.5 | 20.3 |
| 0.06 | 72.0 | 36.0 | 24.0 |
| 0.08 | 88.0 | 41.0 | 24.5 |

Figure 1. Fibrous suspensions after 1 h of the quiescent period: (a) stable suspension and (b) unstable suspension.
The main advantage of the RSM-BBD approach is the ability to optimize the response of multiple variable processes. The systems, analyze the two-variable interaction effects of the model. A polymer concentration, fiber concentration, and temperature, were investigated in various polymeric water-based fluids (CMC, PAM, and XG suspensions) with fiber lengths of 12.5 and 3 mm. Based on the BBD method, 15 sets of experimental trials (Table 5) were required for each fiber length. In total, 90 experimental trials were required considering three different polymers and two fiber lengths. Experimental runs were randomized to minimize the error and exclude any bias, while all conditions were kept constant.

A model of second-order polynomial equations was used to predict the relationship between the factors and stability as a function of polymer concentration, fiber concentration, and temperature. The equation is shown in eq 2

\[ Y = n_0 + n_1X_1 + n_2X_2 + n_3X_3 + n_4X_1^2 + n_5X_2^2 + n_6X_3^2 + n_7X_1X_2 + n_8X_1X_3 + n_9X_2X_3 \]

where \( Y \) is the response variable; \( A, B, \) and \( C \) are independent variables; \( n_0 \) is a model constant variable; \( n_1, n_2, \) and \( n_3 \) are linear coefficients; \( n_4, n_5, \) and \( n_6 \) represent the quadratic effects; and \( n_7, n_8, \) and \( n_9 \) represent interaction effects of the model.
Table 8. Regression Coefficients and P-Values for the 3 mm Fibers

| term | CMC (Y₁) | P-value | PAM (Y₂) | P-value |
|------|----------|---------|----------|---------|
| n₀** | −43.74   | 0.000   | −46.21   | 0.000   |
| X₁** | 49.896   | 0.000   | 50.350   | 0.000   |
| X₂***| −38      | 0.704   | 14.7     | 0.671   |
| X₃***| −0.012   | 0.419   | 0.0038   | 0.592   |
| X₄²  | −3.974   | 0.000   | −4.0004  | 0.000   |
| X₅²  | 332      | 0.740   | −84      | 0.903   |
| X₆²  | 0.00006  | 0.958   | 0.000171 | 0.835   |
| X₇X₈ | 2.41     | 0.770   | 0.96     | 0.866   |
| X₇X₉ | 0.00000  | 1.000   | −0.00318 | 0.613   |
| X₈X₉ | −0.258   | 0.805   | −0.317   | 0.665   |

**n₀ regression constant, ** X₁ polymer cont., *** X₂ fiber conc., and **** X₃ temperature.**

3. RESULTS AND DISCUSSION

3.1. Model Regression. Stability results are summarized in Table 6; the data represent the experimental conditions and the observed stability in percentages.

A second-order polynomial regression model was generated to determine the relationship between the factors and the stability response Y₁, Y₂, and Y₃ of 12.5 mm fiber in CMC, PAM, and XG, respectively. The results are shown below:

\[
Y_1 = -61.7 + 48.88X_A + 231X_B + 0.531X_C - 3.482X_A^2 \\
+ 3899X_B^2 - 0.00464X_C^2 - 99.4X_AX_B \\
- 0.0070X_AX_C - 0.0007X_BX_C
\]

(3)

\[
Y_2 = -68.7 + 41.88X_A + 892X_B + 0.96X_C - 2.68X_A^2 \\
- 10761X_B^2 - 0.0181X_C^2 - 63.1X_AX_B \\
- 0.00359X_AX_C + 14.9X_BX_C
\]

(4)

\[
Y_3 = 136.8 + 3.62X_A - 930X_B - 0.77X_C - 1.537X_A^2 \\
+ 6863X_B^2 - 0.082X_C^2 + 39.0X_AX_B + 0.2597X_AX_C \\
- 0.0X_BX_C
\]

(5)

The coefficients of the regression equations with a positive sign indicate a synergistic effect, whereas the negative sign of the coefficients represents the antagonistic effect on the stability response. In other words, the coefficients with positive signs have a positive effect on stability, while terms with a negative sign are of negative impact. For instance, in eq 3, linear terms, X₄X₅ and X₆X₇, and the quadratic term X₄² have positive signs, which reflects their influence toward increasing the stability. Other coefficients of the equation with negative signs such as second-order terms X₄² and X₅² have a negative effect on the response, leading to a decrease in stability as these terms decrease.

The probability P-value is used to determine the significance of coefficients and the influence of the combined terms of the interaction. Coefficients with p-values smaller than 0.05 tend to have a significant effect on the response. Table 7 shows the regression terms and their corresponding p-values. For example, Y₁ model significant terms are n₀, X₁, X₂², and X₉X₈, where all remaining insignificant terms could be removed without affecting model prediction.

3.2. Model Validation. The correlation plots of model predictions against experimental results for responses Y₁ to Y₃ are shown in Figure 2. Data of the coefficient of determination indicate that the stability-dependent variable can be predicted through modeled equations employing the intended independent variables. Figure 2e shows only one XG plot, as the XG second regression model was not established. All figure coefficients of determination reflect good model prediction against experimental runs, with R² values larger than 0.90. All model predictions are bounded between 0 and 100 percentages, as values above or below this range do not reflect any physical meaning.

In order to further validate the generated models, four conditions (I–IV) were selected based on calculations of the center point between the high, mid, and low levels of factors (Table 2). Consequently, data points X₄X₅ and X₆X₇ presented in Table 9 (polymer concentration, fiber concentration, and temperature) were inputted in the models, and the outputs were compared to experimental results conducted under the same conditions. The points are in descending orders for all parameters. For instance, point I has the highest concentration (71%), while point IV has the lowest concentration (3.6%).

Stability prediction was obtained using 3 for 12.5 mm fibers and eqs 6 and 7 for 3 mm fibers. Table 10 compares the fibers’ experimental and predicted stabilities and the corresponding error percentage.

A good agreement between experimental and predicted values is found with all points below a 20% error margin. The lowest error values are observed at point I, and the error gradually increases as the test data approach the lower constraints (−1) of factors.
3.3. Response Surface Analysis. The regression equations, predicting the effect of fluid concentration, fiber concentration, and temperature on fiber stability, were explained by 3D response surface plots. The response surface plots were generated by plotting two factors over their respective ranges, while the third factor was kept at a constant value: 0.45 wt % for fluid concentration, 52.5 °C for temperature, or 0.05 wt % for fiber concentration. The results are demonstrated in Figures 3−5. Stability results were bounded between 0 and 100%, as any

![Figure 2. Model predicted response against experimental response for the stability of (a) 12.5 and (b) 3 mm fiber in the CMC fluid; (c) 12.5 and (d) 3 mm in the PAM fluid; and (e) 12.5 mm in the XG fluid.](image-url)

| Table 9. Model Validation Data Points |
|--------------------------------------|
| polymer conc. ($X_A$) | fiber conc. ($X_B$) | temperature ($X_C$) |
| condition I | 7.1 | 0.0725 | 73.1 |
| condition II | 6.25 | 0.065 | 66.25 |
| condition III | 4.5 | 0.05 | 52.5 |
| condition IV | 3.6 | 0.0425 | 45.6 |
Table 10. Experimental Confirmation

| response          | 12.5 mm fibers in CMC (Y₁) | 3 mm fibers in CMC (Y₂) | 12.5 mm fibers in PAM (Y₃) | 3 mm fibers in PAM (Y₄) | 12 mm fibers in XG (Y₅) |
|-------------------|-----------------------------|-------------------------|----------------------------|-------------------------|-------------------------|
| Conditions        | I                           | II                      | III                        | IV                      | I                       |
| model prediction  | 100.00                      | 100.00                  | 99.98                      | 84.10                   | 100.00                  |
| experimental      | 100.00                      | 100.00                  | 100.00                     | 100.00                  | 100.00                  |
| error %           | 0.00                        | 0.00                    | 0.02                       | 15.90                   | 0.00                    |
| response          | 3 mm fibers in CMC (Y₂)     | 12.5 mm fibers in PAM (Y₃) |
| conditions        | I                           | II                      | III                        | IV                      |
| model prediction  | 100.00                      | 100.00                  | 98.68                      | 82.84                   |
| experimental      | 98.80                       | 100.00                  | 100.00                     | 98.94                   |
| error %           | 1.21                        | 0.00                    | 1.32                       | 16.27                   |
| response          | 12.5 mm fibers in PAM (Y₃) |
| conditions        | I                           | II                      | III                        | IV                      |
| model prediction  | 100.00                      | 100.00                  | 98.79                      | 82.87                   |
| experimental      | 99.48                       | 100.00                  | 100.00                     | 98.40                   |
| error %           | 0.00                        | 0.52                    | 1.21                       | 15.78                   |
| response          | 3 mm fibers in PAM (Y₄)     | 12 mm fibers in XG (Y₅) |
| conditions        | I                           | II                      | III                        | IV                      |
| model prediction  | 100.00                      | 100.00                  | 99.73                      | 99.22                   |
| experimental      | 100.00                      | 100.00                  | 100.00                     | 100.00                  |
| error %           | 0.00                        | 0.00                    | 0.27                       | 0.78                    |

lower or higher percentages imply same physical characteristics. Increasing the CMC concentration increases the stability of the fibers (Figure 3b,c). The stability of 80% can be reached with 0.28 and 3.45 CMC concentrations, respectively, for 12.5 and 3 mm fibers. The same trend can be observed in Figure 3e,f despite the change in fiber length. Increasing the fiber concentration or temperature shows a negligible increase in fiber stability; therefore, the CMC concentration effect is the dominating factor for fiber stability.

Figure 4 shows fiber suspension in the PAM solution. Temperature, fiber concentration, and fiber length effects are insignificant compared to the polymer concentration effect; increasing the polymer concentration increases the fiber suspension. A stability of 80% can be achieved with a concentration of 0.44 and 3.45, respectively, for 12.5 and 3 mm fibers. At a fixed polymer concentration, the temperature effect becomes more significant, as a gradual increase in temperature decreases fiber stability, making it unstable for 12.5 mm fibers. Rheological tests (Figure 6) reveal that high concentrations of PAM are sensitive to temperature change. An increase in PAM suspension temperature leads to a reduction in suspension viscosity, which is responsible for fiber suspension.

XG has the highest viscosity compared to other suspensions (Figure 6). The temperature effect on the viscosity only appears beyond 50 °C; therefore, XG is preferable for high-temperature conditions. Fiber stability in XG is also dominated by the polymer concentration. At a high temperature of 80 °C, low XG concentration is not capable of holding fibers in the suspension, yet the increase in polymer concentration can overcome the temperature effect, resulting in a stable suspension. Fiber concentration is found to have null effect on the XG system stability; increasing the fiber concentration shows a negligible effect on system stability at high and low temperatures and concentrations (Figure 5).

The fibers’ aspect ratio has a distinctive effect on stability along with the temperature and polymer concentration. A comparison of Figure 3a,d shows that the fiber aspect ratio effect differs depending on fiber concentration. At low fiber concentration, the 12.5 mm fibers tend to resist instability induced by temperature rise before reaching a breaking point. Subsequently, the stability decreases; however, the decrease is insufficient to destabilize the system. On the other hand, 3 mm fibers show a similar trend with no resistance to temperature change. At high fiber concentration, 12.5 mm fibers show better stability at elevated temperatures, while for the 3 mm fibers, lowest stability is observed at high fiber concentration and high temperature, yet it is also within the stable range. This paradox of small changes is explained by fiber entanglement tendency; 12.5 mm fibers have a higher probability of forming a structured fibrous network due to their higher chances of entanglement. The structured network formed aids the suspension within the system. In contrast, it is harder for 3 mm fibers to form a network, yielding in an increased amount of individually dispersed fibers that float to the pre-defined unstable region.

3.4. Optimization. Desirability function is a common method used to assess the optimization response surface. The predicted values obtained from the response are transformed into a dimensionless scale d. Desirability function ranges between d = 0 and d = 1, with zero indicating unacceptable response values and unity reflecting a completely desirable response. The optimization was accomplished by targeting 100% stability at ambient (Table 11) and elevated temperatures (Table 12). Optimization results, desirability values, and suspensions are summarized in the tables below.

All desirability values were acceptable (d > 0.95) with the achieved targeted 100% stability. Response results confirm the dominating effect of polymer concentration on stability. Figures 7 and 8 illustrate the factors that influence fiber stability optimization. The vertical straight line for each factor reflects the selected factor level, and the dotted horizontal line reflects the predicted response value. At high polymer concentration, fiber and temperature curves flatten, diminishing factor interactions. Figure 7a,b reveals that the rise in temperature results in higher stability sensitivity with respect to fiber wt % change, where fiber concentration curvature increases. Figure 8a,b illustrates the fiber aspect ratio effect on stability optimization. Fibers with smaller aspect ratios show stability independence to fiber concentration and temperature with total dependency on polymer concentration.

4. CONCLUSIONS

The fiber stability was investigated in this study using Box–Behnken design to obtain models of fiber stability as a function of fluid concentration, fiber concentration, and temperature. The fiber stability was investigated using two fiber lengths in several water-based fluids (CMC, PAM, and XG). The results can be summarized as follows:

- Models showed that the base fluid concentration had a dominant effect on fiber stability. The increase in fluid concentration enhances system stability. At low fluid concentrations, temperature impact on system stability becomes more significant; increasing system temperature lowers the suspension viscosity and destabilizes the system. Therefore, the effect of temperature is associated with polymer concentration.
The rheological measurement showed that some polymers could be sensitive to elevated temperatures, changing their suspension rheological properties. CMC and PAM showed high sensitivity to temperature changes, while XG showed less sensitivity. The increase in temperature up to 50 °C did not affect XG viscosity.

Figure 3. Effect of (a) temperature and fiber concentration, (b) temperature and fluid concentration, and (c) fiber concentration and fluid concentration on the stability of the fiber length 12.5 mm in the CMC fluid and effect of (d) temperature and fiber concentration, (e) temperature and fluid concentration, and (f) fiber concentration and fluid concentration on the stability of fiber length 3 mm in the CMC fluid.
Although XG exhibits good thermal sensitivity, its high viscosity restricts its usage within wellbore hydraulic limits. Hence, XG can be used in small amounts to aid a non-stable system.

Figure 4. Effect of (a) temperature and fiber concentration, (b) temperature and fluid concentration, and (c) fiber concentration and fluid concentration on the stability of the fiber length 12.5 mm in the PAM fluid and effect of (d) temperature and fiber concentration, (e) temperature and fluid concentration, and (f) fiber concentration and fluid concentration on the stability of fiber length 3 mm in the PAM fluid.
Stability experiments on 3 mm fibers in the XG suspension exhibited complete stability for all experimental runs; therefore, it was excluded from the regression.

- Fibers of high aspect ratios showed better resistance to suspension destabilization. The increased length increases the possibility for individual fibers to entangle, forming a structured network. In contrast, short fibers tend to escape network formation and become more sensitive to factors influencing system stability.

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**Figure 5.** Effect of (a) temperature and fiber, (b) temperature and fluid concentration, and (c) fiber and fluid concentration on the stability of the fiber length 12.5 mm in the XG fluid.

**Figure 6.** Initial viscosity at different concentrations of (a) CMC, (b) PAM, and (c) XG fluids as a function of fluid temperature at a low shear rate (10/s).
Table 11. Response Optimization and Desirability at Ambient Temperature

| response | goal | lower | target | upper | predicted response | desirability | polymer (vol %) | fiber (wt %) | temp. (°C) |
|----------|------|-------|--------|-------|---------------------|--------------|----------------|-------------|------------|
| Y₁       | target | 0.000 | 100.000 | 101.000 | 100.000             | 1.000        | 4.500          | 0.066       | 25.000     |
| Y₂       | target | 0.000 | 100.000 | 101.000 | 100.000             | 0.999        | 6.232          | 0.075       | 25.000     |
| Y₃       | target | 0.000 | 100.000 | 101.000 | 100.000             | 1.000        | 1.692          | 0.080       | 25.000     |
| Y₄       | target | 0.000 | 100.000 | 101.000 | 100.000             | 1.000        | 4.534          | 0.020       | 25.000     |
| Y₅       | target | 0.000 | 100.000 | 101.000 | 100.000             | 1.000        | 4.544          | 0.020       | 25.000     |

Table 12. Response Optimization and Desirability at Elevated Temperature

| response | goal | lower | target | upper | predicted response | desirability | polymer (vol %) | fiber (wt %) | temp. (°C) |
|----------|------|-------|--------|-------|---------------------|--------------|----------------|-------------|------------|
| Y₁       | target | 0.000 | 100.000 | 101.000 | 100.000             | 1.000        | 4.500          | 0.063       | 80.000     |
| Y₂       | target | 0.000 | 100.000 | 101.000 | 94.500              | 0.974        | 6.373          | 0.078       | 80.000     |
| Y₃       | target | 0.000 | 100.000 | 101.000 | 100.000             | 1.000        | 5.578          | 0.020       | 80.000     |
| Y₄       | target | 0.000 | 100.000 | 101.000 | 100.000             | 1.000        | 4.578          | 0.020       | 80.000     |
| Y₅       | target | 0.000 | 100.000 | 101.000 | 100.000             | 1.000        | 4.540          | 0.020       | 80.000     |

Figure 7. Y₃ (PAM) optimization response at (a) 25 and (b) 80 °C.

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Notes

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Figure 8. Y2 and Y5 (PAM) optimization response for (a) 12.5 and (b) 3 mm fibers, respectively.
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