UDC 622.276.66:661.185 doi: 10.20998/2079-0821.2026.01.11

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INVESTIGATION OF TRIETHANOLAMINE AS A BREAKER ADDITIVE FOR HYDRAULIC FRACTURING FLUIDS

This study focuses on a comprehensive investigation of the rheological properties and chemical activation mechanisms of triethanolamine (TEA) for its application as a specialized breaker additive in fracturing fluids during hydrocarbon production stimulation via hydraulic fracturing (HF). The proposed technology is specifically designed for implementation in newly drilled wells or those undergoing complex workover and well intervention operations. The primary objective of the research is to evaluate the effectiveness of TEA as a catalytic activator for the primary breaker, ammonium persulfate (APS), in reservoirs characterized by relatively low-static temperatures (down to 38–40°C). At such thermal conditions, conventional oxidizing breakers often exhibit insufficient reactivity, leading to incomplete gel degradation and subsequent impairment of fracture conductivity.

The experimental part of the work involved the development of a stable base crosslinked borate gel formulation consisting of technical water, guar-based thickener (2.4 kg/m³), and a synergistic blend of biocides, clay stabilizers, and surfactants. Utilizing a Brookfield Model PVS High-Pressure Rheometer, the study analyzed the viscosity-time profiles of various formulations under simulated reservoir conditions. Results demonstrate that the inclusion of TEA at an optimal loading of 0.5 l/m³ successfully triggers the APS decomposition, ensuring that the fluid retains a target proppant-carrying viscosity of 200 cP for the required pumping duration (approx. 45 minutes) while achieving a near-total viscosity reduction to 10–20 cP post-treatment.

Furthermore, the research establishes a critical correlation between increased breaker loadings and the acceleration of the fluid "break" profile, which is essential for optimizing the final stages of the fracturing treatment (flush and tail-in).

Keywords: Hydraulic fracturing (HF); well stimulation; simulation software; fracturing fluids (frac fluids); fluid rheology

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ДОСЛІДЖЕННЯ ТРИЕТАНОЛАМІНУ В ЯКОСТІ ДЕСТРУКТИВНОЇ ДОБАВКИ ДО ТЕХНОЛОГІЧНОЇ РІДИНИ ГІДРАВЛІЧНОГО РОЗРИВУ ПЛАСТА

Це дослідження зосереджене на всебічному вивченні реологічних властивостей та хімічних механізмів активації триетаноламіну (ТЕА) для його застосування як спеціалізованої добавки-деструктора в технологічних рідинах під час стимулювання видобутку вуглеводнів методом гідравлічного розриву пласта (ГРП). Запропонована технологія спеціально розроблена для впровадження в нових пробурених свердловинах або в тих, що проходять складні операції з капітального ремонту та свердловинного втручання. Основною метою дослідження є оцінка ефективності ТЕА як каталітичного активатора основного деструктора — персульфату амонію (APS) — у пластах, що характеризуються відносно низькими статичними температурами (до 38–40 °C). За таких температурних умов традиційні окиснювальні деструктори часто виявляють недостатню реакційну здатність, що призводить до неповної деградації гелю та подальшого погіршення провідності тріщини.

Експериментальна частина роботи включала розробку стабільної базової рецептури зшитого боратного гелю, що складається з технічної води, згущувача на основі гуару (2,4 кг/м³) та синергічної суміші біоцидів, стабілізаторів глин і поверхнево-активних речовин. Використовуючи високотискний реометр Brookfield моделі PVS, у дослідженні проаналізовано профілі залежності в'язкості від часу для різних рецептур за змодельованих пластових умов. Результати демонструють, що включення ТЕА в оптимальній концентрації 0,5 л/м³ успішно запускає розпад APS, гарантуючи, що рідина зберігає цільову в'язкість понад 200 сП для ефективного перенесення пропанту протягом необхідного часу закачування (приблизно 45 хвилин), досягаючи при цьому майже повного зниження в'язкості до 10–20 сП після обробки.

Крім того, дослідження встановлює критичну кореляцію між збільшенням завантаження деструктора та прискоренням профілю руйнування рідини, що є суттєвим для оптимізації заключних стадій обробки ГРП (промивка та фінальні пачки пропанту).

Keywords: гідравлічний розрив пласта, інтенсифікація видобутку вуглеводнів, програмне забезпечення, рідини гідророзриву, реологія рідин.

1. Introduction

In recent years, hydraulic fracturing (HF) has become a cornerstone technology among hydrodynamic (hydromechanical) stimulation methods for enhancing the inflow of reservoir fluids in both newly completed wells and those following workover operations. The HF process is based on creating a high-conductivity fracture to increase fluid recovery rates. Before proceeding with a HF treatment, a comprehensive technical and economic feasibility study is conducted for the candidate well: this includes evaluating the geological and technological potential, forecasting the incremental production rate post-HF, and selecting optimal treatment parameters and injection regimes.

The HF operations involve the use of fracturing fluids (typically water-based fluids) integrated with various additives for rheology control, and propping agents (proppant or quartz sand) to maintain the width of the created high-conductivity fracture. Chemical reagents represent a significant portion of the total operational expenditure (OPEX): costs associated with fracturing fluids have accounted for 12% of the total HF expenditures over the last decade [1].

The rheological properties of HF fluids describe their behavior under mechanical shear stress. These include characteristics such as viscosity, density, structure, and thermal stability, which determine how the medium deforms and flows under external forces. Specifically, these properties dictate the success of proppant transport, as well as fracture geometry development and maintenance. Chemical additives are utilized precisely to tailor the fluid rheology to specific geological and reservoir (HPHT) conditions.

As the frequency of HF operations increases, so does the demand for complex studies on HF fluid behavior under varying conditions and additive concentrations. Comprehensive laboratory testing is essential to provide the necessary data for such analysis.

2. Literature Review

Recent global studies emphasize that polymeric thickeners - such as guar derivatives or acrylamide copolymers - provide the necessary viscosity for hydraulic fracturing (HF) fluids; however, their rheological properties are highly dependent on reservoir conditions, specifically temperature and salinity (mineralization). For instance, Xiaoqin Cao et al. compared a synthetic salt-tolerant polyacrylamide (PAA) with a guar-based fluid under High-Temperature/High-Salinity (HTHS) conditions. They found that while both systems provided effective thickening and exhibited thermal stability, the guar-based gel left significant residue after breaking, whereas the PAA required high concentrations and showed poor proppant-carrying capacity. Nevertheless, direct chemical crosslinking of PAA with zirconium in a saturated solution significantly enhanced the rheology: viscosity increased substantially, and thermal and shear stability were markedly superior compared to the base form [2].

Hui Xin et al. demonstrated that salts (Na^+, Ca^{2+}) typically cause the molecules of hydrolyzed polyacrylamide (HPAM) to coil, leading to a sharp decline in viscosity. However, the addition of an organic zirconium crosslinker and a pH buffer created a gel that maintained a viscosity of ≈60–77 mPa·s at temperatures of 180–200 °C, even in mineralized solutions [3].

For seawater-based applications, Amro Othman et al. utilized a guar-derivative polymer combined with a zirconium crosslinker and a high-pH chelating agent (tetrasodium glutamate diacetate – GLDA). By sequestering hardness ions and increasing the pH, this system maintained nearly the same viscosity in seawater as in fresh water. Furthermore, the zirconium crosslinker initiated gelation immediately at room temperature, eliminating the need for pre-heating required in demineralized water [4].

In parallel, novel polymers are being developed. Shenglong Shi et al. synthesized an acrylamide copolymer featuring dual hydrophobic "tails" and a polymerized non-foaming surfactant. The resulting thickener (0.5% ASDM solution) exhibited "salt-induced thickening"-its viscosity in 100,000 mg/L brine reached ~175.9 mPa·s, doubling that of the surfactant-free control. The robust associative network provided ASDM with high viscoelasticity and thermal resistance, recovering >99% of its initial viscosity after intensive shearing [5].

Furthermore, researchers are investigating viscoelastic surfactants (VES) and hybrid systems with metallic nano-additives. Saber Mohammadi et al. showed that the introduction of metal oxides (Fe_2O_3, MgO, ZnO) significantly improves the rheology of VES-hydrogels. Specifically, Fe_2O_3 nanoparticles (500 ppm) yielded the maximum effect: at 25 °C, fluid viscosity rose to ≈169.6 cP, and the gel stability time at 85 °C increased from ~7.8 to ~17.8 hours. This is attributed to Fe_2O_3 binding the ends of micelles and increasing the number of entanglement points, which reinforces the structure and prevents rapid thermal degradation [6-8].

Similarly, Shenglong Shi et al. developed a novel polymeric friction reducer (SAMD) incorporating sulfonated and hydrophobic monomers along with SiO_2 nanoparticles. This product dissolved rapidly even at 80,000 mg/l salinity and provided >70% drag reduction at 120 °C in 100,000 mg/L brine. After repeated shearing, the system almost completely recovered its initial viscosity; after 120 min of shear at 140 °C, the viscosity remained at ~95.5 mPa·s (1.4 wt%). This was achieved because sulfonate groups mitigate the impact of salt ions, hydrophobic sections form temporary associative bonds, and SiO_2 further reinforces the polymer chains-collectively creating a robust structure capable of withstanding extreme HTHS conditions [9-12].

Consequently, current global research indicates that the integration of modified polymers, crosslinkers, surfactants, and nanomaterials enables the formulation of HF fluids with enhanced rheological properties and stability under extreme conditions (HPHT and high salinity).

3. Objective

The primary objective of this study is to justify the application of triethanolamine (TEA) as a breaker activator for hydraulic fracturing (HF) fluids. TEA is intended to activate the primary oxidizing breaker (ammonium persulfate, APS) at lower reservoir temperatures (down to 40°C), thereby expanding its operational temperature range. This is critical because the conventional activation threshold for ammonium persulfate starts at 49°C, whereas the static bottomhole temperature (BHT) of the target candidate well for which the formulation is being optimized is only 38°C.

4. Main Body: Experimental Setup

To investigate the rheological properties of the fracturing fluid, a Brookfield Model PVS Rheometer equipped with specialized Rheovision software was utilized.

The design of the Brookfield sensor is highly sensitive to minor fluctuations in viscosity, transmitting the torque signal from the pressure-retaining zone without friction. The external cylinder (sample cup) is driven by a stepper motor at speeds ranging from 0.05 to 1,000 RPM. A temperature probe, with an operating range of -40 to +260 °C, measures the temperature directly within the test fluid. The sensor system remains unaffected by changes in pressure or temperature. Fig. 1 illustrates the schematic diagram of the rheometer and its core components.

A heating/cooling bath maintains the sample at a user-defined temperature. The sample cup is submerged in the bath medium, facilitating heat transfer to or from the sample through the cup walls. Certain types of heating/cooling baths can be controlled synchronously with the instrument via the Rheovision software interface.

This integration allows precise thermal regulation during testing, ensuring that temperature-dependent viscosity variations are accurately captured. Additionally, the closed-system design minimizes external disturbances, providing stable conditions for evaluating the fluid's behavior under simulated downhole environments. These features collectively enhance the reliability and reproducibility of the rheological measurements.

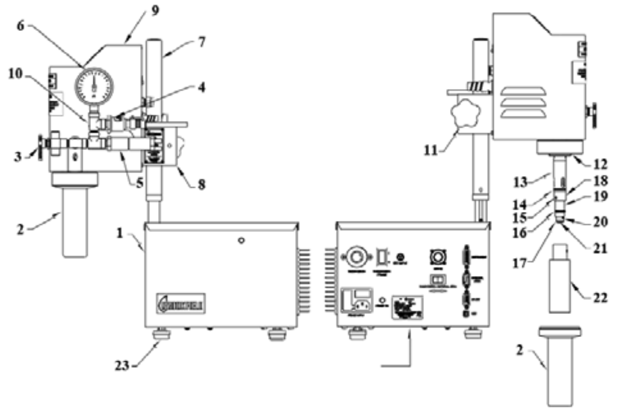

Figure 1 – Components of the brookfield model PVS 230 rheometer

1 - PVS Electronics Assembly (115/230V AC Thermal Bath); 2 - Sample Cup; 3 - 1-Piece 3-Way Ball Valve (1/8 inch FNPT); 4 - Pressure Transducer (1000 PSI); 5 - Pressure Relief Valve (PRV); 6 - Pressure Gauge; 7 - Vertical Support Rod; 8 - PVS Rheometer Head Clamp; 9 - PVS Rheometer Head Cover; 10 - Outer Tee Assembly; 11 - Head Clamp Knob; 12 - Knurled Ring; 13 - Mounting Tube; 14 - Upper Spring Seal; 15 - Screw (2-56 x 1/4); 16 - Beveled Coil Spring; 17 - Lower Spring Seal; 18 - Retaining Bushing; 19 - Temperature Probe Housing; 20 - Dowel Pin; 21 - Temperature Measurement Device (RTD) Cup Assembly; 22 - Stator / Bob (B1, B2, or B5 geometry); 23 - Adjustable Leveling Foot.

Fig. 2 shows the Brookfield Model PVS Rheometer in its operational mode, with the sample cup lowered into the thermal bath to simulate downhole (reservoir) conditions.

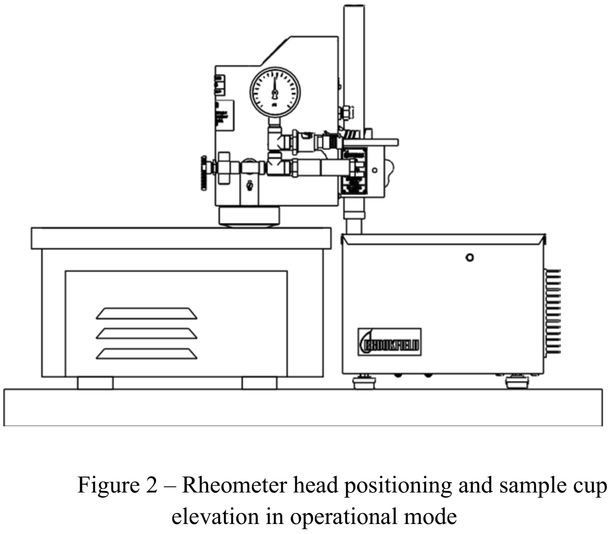

Figure 2 – Rheometer head positioning and sample cup elevation in operational mode

The Rheovision software enables comprehensive control over the rheometer's operation, including data acquisition (DAQ), storage, retrieval, printing, plotting, and analysis. Key features of Rheovision include: an intuitive and user-friendly Graphical User Interface (GUI); background data acquisition (utilizing MS-Windows multitasking capabilities); real-time data plotting during acquisition; background printing of data, charts, and test sequences; mathematical analysis of captured datasets; integrated control of auxiliary Brookfield Engineering Labs thermal baths; calculation of industry-standard parameters (e.g., API Power Law calculations for the oil and gas industry).

The Dashboard provides the following functionalities: real-time monitoring of critical parameters: apparent viscosity, rotational speed (RPM), percent torque, shear stress, shear rate, sample temperature, bath temperature, and pressure; connectivity status monitoring for the PVS unit and thermal bath (Green light indicates an active connection; red light signals a disconnection); torque calibration via the "Zero Torque" button; rotational speed adjustment using the "Set Speed" function; bath temperature regulation via the "Set Temperature" command; bob (spindle) selection and viewing of specific bob geometry constants.

The selection of Triethanolamine (TEA) is justified by its established use in the oil and gas industry. TEA [structural formula: $(HO\text{-}CH_2CH_2)_3N$ or $C_6H_{15}NO_3$] is a colorless, water-soluble tertiary amine. It combines hydroxyl and amino groups, providing simultaneous alkaline, chelating, and surfactant properties. TEA is conventionally used as a thermal stabilizer in HF operations for high-temperature reservoirs (100°C) and as a precursor in the synthesis of certain crosslinkers.

The formulation optimization will be tailored specifically for the candidate well, the initial parameters of which are summarized in Table 1.

Table 1. Candidate Well Baseline Data for Hydraulic Fracturing (HF)

№	Parameter	Value	Unit
1	Total Depth	950	m
2	Production Casing (OD)	177,8	mm
3	Production Casing Wall Thickness	10,36	mm
4	Production Casing Setting Depth	950	m
5	Production Tubing (NKT) OD	88,9	mm
6	Production Tubing Wall Thickness	6,45	mm

7	Production Tubing Setting Depth	836	m
8	Perforation Interval	870-895	m
9	Perforation System / Shot Density	Dynawell 39g DP3 St HMX (18 spf)	-
10	Reservoir Porosity	10,5	%
11	Permeability (k)	0,5	mD
12	Net Pay Thickness (h)	5	m
13	In-situ Fluid Viscosity	0,012619	mPa·s
14	Gas-Oil Ratio (GOR)	0,91	-
15	Reservoir Pressure (Current)	50	atm
16	Reservoir Temperature	38	°C
17	Inclination (Zenith Angle)	0,75	°

During hydraulic fracturing (HF) operations, the crosslinked gel serves to initiate and propagate the fracture while facilitating proppant placement. To maintain stable proppant-carrying capacity, the crosslinked gel within the fracture must retain a viscosity of 200 cP throughout the entire injection period [8]. Failure to maintain this threshold leads to non-uniform proppant distribution, causing proppant bridging within the fracture. This ultimately results in a "screen-out" (STOP), characterized by a rapid spike in tubing pressure.

The breaker, as the name implies, is responsible for the degradation of the crosslinked gel. However, the concentration must be precisely engineered to prevent premature fluid break. During the fracture initiation and propagation stages, the minimum breaker concentration is typically injected. If the gel fails to degrade post-treatment, it significantly impairs fracture conductivity. Due to its residual viscosity, such a gel becomes difficult or even impossible to flow back (lift) to the surface.

It is worth highlighting the primary advantage of encapsulated breakers: they provide "polishing" degradation after fracture closure. The closure pressure crushes the breaker capsules, releasing their contents (in this case, dry ammonium persulfate). For the liquid phase, a 15% aqueous solution of ammonium persulfate is utilized at a concentration of 2 l/m^3.

The average pumping time for the main fracture treatment is approximately 45 minutes. Therefore, it is essential to optimize a crosslinked gel formulation that maintains a viscosity above 200 cP for at least 45 minutes and subsequently undergoes complete degradation (down to 10–20 cP) over time.

The base fluid formulation consists of the following components: process water; BAK-1000 biocide – 0.01 kg/m^3; Polyflos G8F guar gum – 2.4 kg/m^3; CS-1 clay stabilizer – 3 l/m^3; TN-6190 surfactant/de-emulsifier – 1 l/m^3; and WXL-100L instant borate crosslinker – 1.6 l/m^3.

To evaluate TEA as a breaker activator, investigations were conducted on the crosslinked gel with varying TEA concentrations: 0 (control), 0.5, and 1 l/m^3. The first set of test fluids (Formulation 1) includes: process water (25°C); BAK-1000 biocide – 0.01 kg/m^3; Polyflos G8F guar – 2.4 kg/m^3; CS-1 clay stabilizer – 3 l/m^3; TN-6190 surfactant + de-emulsifier – 1 l/m^3; WXL-100L instant borate crosslinker – 1.6 L/m^3; liquid breaker (15% ammonium persulfate solution) – 2 l/m^3; Encapsulated breaker (FEO-1 ammonium persulfate) – 0.1 kg/m^3; Triethanolamine (TEA) – variable loadings: 0, 0.5, and 1 l/m^3. Furthermore, to facilitate the development of the pumping schedule for the target well, it is necessary to test higher concentrations of both liquid and encapsulated breakers for interpolation purposes. Increasing breaker loadings toward the end of the treatment stage (the flush or final proppant stages) accelerates viscosity reduction once the proppant has been placed. The ultimate goal is to ensure efficient flowback to the surface and prevent formation damage (pore plugging). The second set of test fluids (Formulation 2) includes: process water (25°C) – 500 ml; BAK-1000 biocide – 0.01 kg/m^3; Polyflos G8F guar – 2.4 kg/m^3; CS-1 clay stabilizer – 3 l/m^3; TN-6190 surfactant + de-emulsifier – 1 l/m^3; WXL-100L instant borate crosslinker – 1.6 l/m^3; liquid breaker (15% APS solution) – variable loadings: 3 and 4 l/m^3; encapsulated breaker (FEO-1) – variable loadings: 0.2 and 0.3 kg/m^3; triethanolamine (TEA) – fixed loading: 0.5 l/m^3.

5. Research Results and Discussion

Figure 3 presents the baseline stability test results for the crosslinked gel formulation (without the addition of breakers or TEA). As indicated by the plot, the base gel exhibits satisfactory stability, maintaining a viscosity level of approximately 400 cP throughout the 60-minute test period. Figure 4 illustrates the shear stability and rheological recovery of the base crosslinked gel. The data shows that the gel maintains sufficient viscosity under stress and, crucially, demonstrates rapid viscosity recovery following changes in the shear rate. This indicates that the fluid will provide reliable proppant transport to the target zone without risk of premature settling. Furthermore, the consistent viscosity profile suggests that the polymer network remains structurally intact during testing, indicating strong crosslink integrity. The observed resilience under dynamic shear conditions confirms that the gel can withstand operational stresses typical of hydraulic fracturing processes. These results collectively validate the suitability of the base formulation as a reference system for evaluating the influence of additives in subsequent experiments.

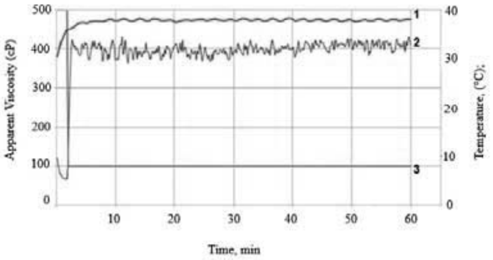

Figure 3 – Stability test results for the base crosslinked gel formulation (without breakers or TEA)
1 - temperature (°C); 2 -apparent viscosity (cP); 3 -shear rate(s^{-1})

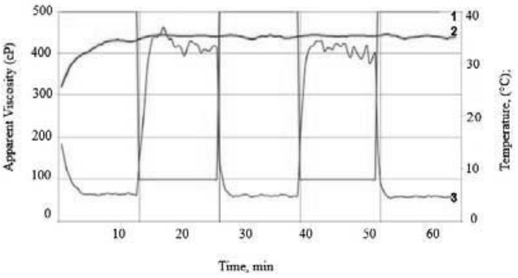

Figure 4 – Shear stability and recovery test results for the base crosslinked gel formulation (without breakers or TEA)
1 - shear rate (s^{-1}); 2 - temperature (°C); 3 - apparent viscosity (cP)

Figure 5 illustrates the test results for the crosslinked gel without TEA (formulation 1). It is observed that the gel maintains a viscosity of 200 cP for 120 minutes (2 hours) but fails to undergo complete degradation. The curve shows a clear plateau effect, with the viscosity stabilizing at approximately 120 cP toward the end of the test.

Figure 6 presents the results for the crosslinked gel with 0.5 l/m³ of TEA added (formulation 1). The plot demonstrates that this formulation maintains the required 200 cP viscosity for 45 minutes-matching the planned pumping time-and subsequently achieves complete degradation within 100–120 minutes. The results for the crosslinked gel with a 1 l/m³ TEA loading (formulation 1) are shown in Figure 7. A trend similar to that in Figure 6 (0.5 l/m³ TEA) is observed: increasing the concentration of the TEA breaker activator did not significantly accelerate or decelerate the degradation rate. The viscosity retention time above 200 cP remained consistent at 45 minutes**.** This suggests that the TEA concentration reaches an effectiveness threshold at 0.5 l/m³, beyond which additional activator does not yield further performance improvements. Therefore, the lower TEA dosage appears to be the more economically optimal choice without compromising the gel-breaking kinetics.

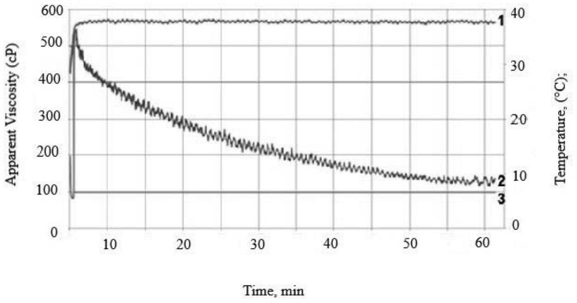

Figure 5 – Test results for the crosslinked gel with breakers and zero TEA loading (0 l/m³)

1 - temperature (°C), 2 – apparent viscosity (cP), 3 – shear rate (s^{-1})

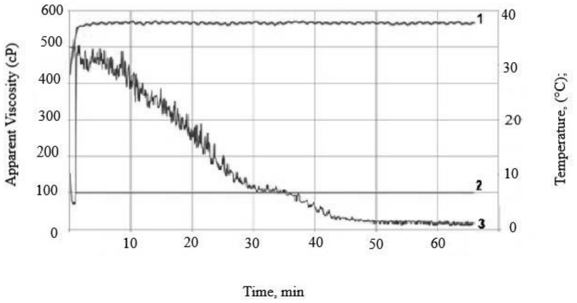

Figure 6 – Test results for the crosslinked gel with breakers and 0.5 l/m³ TEA loading

1 - temperature (°C), 2 – apparent viscosity (cP), shear rate (s^{-1})

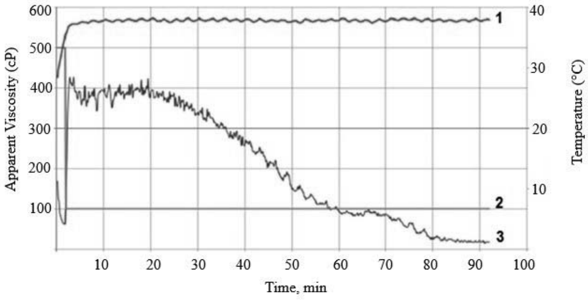

Figure 7 – Test results for the crosslinked gel with breakers and 1 l/m³ TEA loading

1 - temperature (°C), 2 – shear Rate (s^{-1}), 3 – apparent viscosity (cP)

Investigations of crosslinked gels with increased concentrations of both liquid and encapsulated breakers were conducted at a fixed TEA loading of 0.5 l/m³.

As shown in Figure 8, the gel based on formulation 2 (with liquid and encapsulated breaker loadings of 3 l/m³ and 0.2 kg/m³, respectively) maintained the target viscosity of 200 cP for 20 minutes and underwent complete degradation in approximately 50 minutes.

Figure 9 demonstrates that the gel based on formulation 2 (with liquid and encapsulated breaker loadings of 4 l/m³ and 0.3 kg/m³, respectively) retained the target 200 cP viscosity for only 13 minutes, achieving total degradation within approximately 30 minutes.

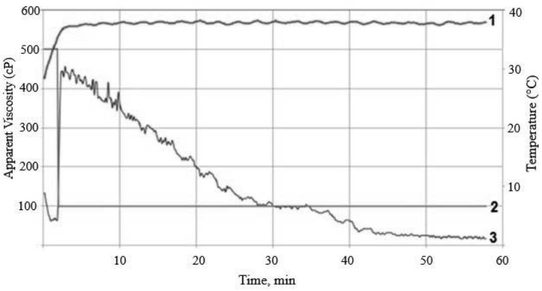

Figure 8 – Test results for the crosslinked gel with combined breaker loadings (liquid: 3 l/m³; encapsulated: 0.2 kg/m³) and 0.5 l/m³ TEA
1 - temperature (°C), 2 – shear rate (s^{-1}), 3 – apparent viscosity (cP)

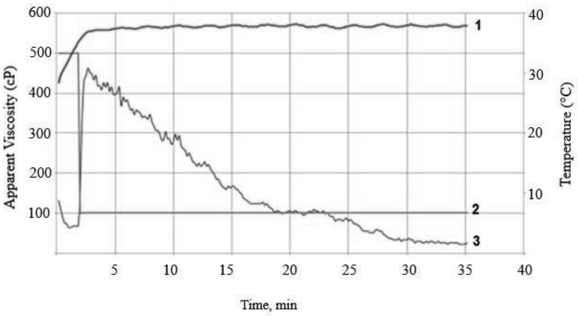

Figure 9 – Test results for the crosslinked gel with combined breaker loadings (liquid: 4 l/m³; encapsulated: 0.3 kg/m³) and 0.5 l/m³ TEA

1 - temperature (°C), 2 – shear rate (s^{-1}), 3 – apparent viscosity (cP)

6. Conclusions

For hydraulic fracturing (HF) operations in a reservoir with a static temperature of 38°C, a robust base gel formulation has been optimized. The system utilizes process water as the base fluid, supplemented with: BAK-1000 biocide (0.01 kg/m³), Polyflos G8F guar (2.4 kg/m³), CS-1 clay stabilizer (3 l/m³), TN-6190 surfactant/de-emulsifier (1 l/m³), and WXL-100L instant borate crosslinker (1.6 l/m³). This base formulation meets all operational requirements, demonstrating excellent thermal stability for 60 minutes and rapid rheological recovery post-shear. These properties ensure superior proppant-carrying capacity and efficient transport to the target zone.

Investigations into the catalytic effect of Triethanolamine (TEA) at loadings from 0 to 1 l/m³ revealed that increasing the TEA concentration from 0.5 to 1 l/m³ (in combination with the primary ammonium persulfate breaker) did not significantly alter the degradation kinetics. The viscosity retention time above 200 cP remained constant at 45 minutes. Consequently, an optimal TEA loading of 0.5 L/m³ is recommended for cost-effective activation at low reservoir temperatures.

Rheological tests involving increased loadings of the primary breakers-liquid (15% APS solution at 3–4 l/m³) and encapsulated (FEO-1 at 0.2–0.3 kg/m³)-with a fixed 0.5 l/m³ TEA loading showed a target viscosity duration of 13 to 20 minutes, with total fluid break achieved within 30 to 50 minutes. A clear correlation was established: higher breaker loadings result in a shorter viscosity plateau and accelerated degradation.

Based on these findings, the following formulations are recommended for field implementation:

1. Fracture initiation and propagation stages: It is recommended to use the crosslinked gel containing: process water, BAK-1000 (0.01 kg/m³), Polyflos G8F (2.4 kg/m³), CS-1 (3 l/m³), TN-6190 (1 l/m³), WXL-100L (1.6 l/m³), liquid APS (2 l/m³), encapsulated APS (0.1 kg/m³), and TEA (0.5 l/m³). This formulation maintains the required carrying capacity during the injection period and achieves complete degradation within the designated timeframe.
2. Proppant placement and final stages: upon reaching the target fracture geometry, breaker loadings should be incrementally increased by interpolating the data from Formulation 2. This ensures rapid viscosity reduction post-placement, facilitating efficient well cleanup and preventing formation damage (pore plugging).

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Дата надходження статті: 06.03.26 р.
Дата прийняття до друку: 10.04.26 р.