Fluid Dynamics &
Materials Processing

Tech Science Press

http://doi.org/10.32604/fdmp.2026.085147

ARTICLE

# Experimental Investigation of Residual Acid Effects on Flushing Efficiency, Rheological Compatibility, and Thickening Behavior in a Novel Pre-Cementing Acidification Process

**Wei Wang[1], Hao Guo[1], Cheng Jian[1], Yi Yu[1], Quanmin Jiang[1] and Chunyu Wang[2,*]**

[1]CNOOC China Limited, Zhanjiang Branch, Zhanjiang, China
[2]School of Materials Science and Engineering, Nanjing Tech University, Nanjing, China
*Corresponding Author: Chunyu Wang. Email: wangchunyu@njtech.edu.cn

Received: 06 May 2026; Accepted: 30 June 2026; Published: 31 July 2026

**ABSTRACT:** To overcome the inherent limitations of conventional post-cementing acidification, including limited acid penetration into the formation and the potential impairment of zonal isolation, a novel pre-cementing acidification approach is proposed. This method aims to remove near-wellbore formation damage before cementing operations. Its feasibility, however, critically depends on the physicochemical compatibility between residual acid and the subsequent cementing fluids, namely spacer fluids and cement slurries. In this study, a comprehensive series of laboratory experiments was conducted to evaluate the effects of residual acid on flushing efficiency, rheological compatibility, and thickening time. The results show that residual acid significantly enhances the ability of spacer fluids to remove drilling fluid filter cakes, increasing the flushing efficiency from 82.61% to 91.90%. In the presence of 2% corrosion inhibitor, increasing the acid dosage further improves flushing performance. Although mild rheological incompatibility is observed between the spacer fluid and the cement slurry, residual acid effectively reduces the R-value, thereby improving fluid compatibility, with a 50% acid concentration providing greater improvement than a 25% concentration. High-temperature and high-pressure tests conducted at 80°C and 150°C show that the thickening times of mixtures containing different acid concentrations and dosages are comparable to, or longer than, that of the neat cement slurry, indicating no risk of flash setting or excessive retardation. These findings demonstrate that the proposed pre-cementing acidification process is compatible with subsequent cementing fluids under the investigated conditions, providing experimental evidence supporting its technical feasibility.

**KEYWORDS:** Pre-cementing acidification; flushing efficiency; rheological compatibility; thickening compatibility; high-temperature and high-pressure

## 1 Introduction

Acidification is one of the core technologies for oil and gas well stimulation. By injecting strong acidic fluids (such as hydrochloric acid or mud acid) into the reservoir to dissolve potential mineral blockages or enlarge flow channels, it effectively restores or enhances reservoir permeability and is widely used for productivity activation in low-permeability and contaminated reservoirs [1–3]. Cementing is a critical engineering process for ensuring wellbore structural stability, preventing inter-zonal channeling, and guaranteeing the long-term safety of oil and gas well production.

In traditional engineering practice, acidification operations are typically scheduled after cementing and perforation. However, for strongly heterogeneous carbonate reservoirs or complex well sections with

severe near-wellbore pollution [4–8], post-cementing acidification faces numerous challenges: on one hand, the barrier of the cement sheath restricts the full contact between the acid and the contaminated zone, limiting stimulation effectiveness; on the other hand, during high-pressure acidification, acid can easily channel along the micro-annulus between the cement sheath and the formation or casing, corroding the cement sheath, compromising zonal isolation, and even inducing safety accidents such as sustained casing pressure (SCP).

To address these limitations, this study proposes an innovative "pre-cementing acidification" operational concept, which involves performing acidification treatment before running casing and cementing [9,10]. The theoretical advantage of this mode lies in its ability to directly contact and remove reservoir damage in the near-wellbore zone, significantly improving acid-rock reaction efficiency. Simultaneously, the acid may alter the formation surface roughness, which has been hypothesized in literature to affect bonding between the cement slurry and the formation [9,10]. However, evaluating the actual mechanical bonding strength and cement-sheath integrity under these conditions requires separate testing and is beyond the scope of this compatibility study.

However, the implementation of this process faces severe fluid compatibility challenges. After acidification is completed, some acid will inevitably remain in the wellbore and near-wellbore zone. When spacer fluids and cement slurries are subsequently injected, this residual acid (mainly composed of hydrogen ions ($H^+$), chloride ions ($Cl^-$), and reaction products such as calcium ($Ca^{2+}$) and magnesium ($Mg^{2+}$) ions) will contact and mix with the alkaline cementing working fluids. If severe incompatibility reactions occur—such as acid-induced degradation of drilling fluid additives leading to flocculation, inducing instantaneous "flash set" or abnormal thickening of the cement slurry, or reducing the strength of the set cement—it will directly result in cementing failure.

Therefore, systematically evaluating the impact of acidification acid on the performance of cementing working fluids and clarifying the rheological behavior and hydration process of fluids under residual acid environments are prerequisites for verifying the feasibility of the "pre-cementing acidification" technology. In view of this, this study simulates the downhole conditions of pre-cementing acidification through laboratory experiments, focusing on the influence of different concentrations and dosages of acid on spacer fluid flushing efficiency, spacer-cement rheological compatibility, and thickening time. The aim is to provide laboratory compatibility data and scientific support for evaluating this novel integrated stimulation-cementing technology.

## 2 Experimental Scheme

To ensure scientific reliability, all laboratory experiments, including flushing efficiency, rheology, and thickening time, were performed in triplicate. The average values are reported, and the relative standard deviation of the measurements was within ±5%.

### *2.1 Materials*

The experimental materials were organized into three categories: cementing working fluids, acidification fluid, and drilling fluid for filter cake preparation.

Cementing working fluids. The cementitious material used was high sulfate-resistant (HSR) Class G oil well cement, manufactured by Zibo Zhongchang Special Cement Co., Ltd., conforming to American Petroleum Institute (API) Specification 10A [11]. All chemical additives were supplied by China National Offshore Oil Corporation (CNOOC). Two types of cementing working fluids were prepared: (1) a spacer fluid, formulated with water, a flushing agent (to break and disperse the drilling fluid filter cake), a weighting

agent (to achieve the required density), a spacer agent (to provide mutual isolation between the drilling fluid and cement slurry), and a defoamer; (2) a cement slurry, formulated with Class G cement, a corrosion inhibitor, a self-healing agent (to seal micro-annuli upon hydration expansion), a retarder (to control thickening time), a fluid loss additive (to minimize filtrate invasion), a dispersant (to improve workability), and a defoamer.

Acidification fluid. A hydrochloric acid (HCl)-based acidification fluid was used, with HCl (with a nominal concentration of 20% active HCl) as the primary active component; the complete formulation of the stock acid solution was not fully characterized in this study. While the residual acid downhole would be partially spent and contain reaction products (such as calcium and magnesium ions), using fresh acid of varying concentrations (25% and 50% dilution of the stock acid) represents a conservative, worst-case scenario. This is because fresh acid possesses a higher hydrogen ion concentration and reactivity compared to spent acid, providing a more rigorous test for fluid compatibility and potential degradation. The stock acid was diluted with water to obtain two target concentrations: 50% and 25% ($v/v$). A compound organic corrosion inhibitor was incorporated at a fixed dosage of 2% (by mass of acid solution) to mitigate tubular corrosion and to provide surfactant assistance during flushing. These concentrations and dosage levels were selected to cover the range of residual acid conditions anticipated in field pre-cementing acidification operations.

Drilling fluid for filter cake preparation. A water-based drilling fluid, representative of field formulations used in the target formations, was employed to prepare standardized filter cakes for the flushing efficiency tests.

### *2.2 Spacer Fluid Flushing Efficiency Test*

The selection of the two-hour soaking period and the chosen acid concentrations (25% and 50% dilutions of the stock acid) was based on typical field acidification operations, where the shut-in or contact time of the acid in the wellbore ranges from 1 to 3 h before cementing fluids are pumped, and the dilution simulates the mixing of the acid with pre-flush spacer fluids downhole. To prepare the filter cake, high-temperature high-pressure (HPHT) filter paper was loaded into the HPHT filter press. An appropriate amount of drilling fluid preheated to 90°C was poured in, and the filter cake was prepared under experimental conditions (500 psi, 90°C) with a fluid loss time of 30 min. The filter paper and filter cake were taken out, the soft, uncompacted cake layer was gently washed off with water, and the mass of the filter paper and cake was weighed. Then, it was fixed on the outer cylinder of a rotary viscometer with a rubber band, and the total weight was recorded. Subsequently, the filter cake was immersed in 400 mL of acid solution (stock acid diluted 1:1 ($v/v$) with water, to which 2% corrosion inhibitor was added, yielding a final concentration of 50%) for 2 h. The weight of the filter cake and filter paper after acid soaking was recorded to quantify the mass dissolved by acid.

The spacer fluid was prepared according to the formulation and stirred in a 90°C atmospheric consistometer for 20 min. It was then poured into the viscometer cup to the scribed line, submerging the entire filter cake. The rotary viscometer was started at 200 rpm, and the filter cake was flushed at cumulative time intervals of 10, 15, 20, and 30 min, with the assembly weighed at each interval. Finally, the filter paper was removed, the residual mud cake on the flushed part was scraped off, and the weights of the cylinder, rubber band, and filter paper were measured separately. The flushing efficiency of the spacer fluid was calculated using the formula:

$$\eta = \frac{m_1 - m_2}{m_1 - m_3} \times 100 \tag{1}$$

where $\eta$ is the flushing efficiency (%); $m_1$ is the weight of filter cake and filter paper (g); $m_2$ is the weight of filter cake and filter paper after spacer fluid flushing (g); and $m_3$ is the weight of the filter paper after scraping off all residual mud cake from the flushed area (g).

### *2.3 Spacer Fluid and Cement Slurry Rheological Compatibility Test*

To evaluate the impact of residual acid on the rheological compatibility between spacer fluid and cement slurry, tests were conducted under atmospheric pressure at 90°C. Five different volume ratios of spacer fluid to cement slurry were set: 5/95, 25/75, 50/50, 75/25, and 95/5. Two acid concentrations (50% and 25%) were selected, with five acid dosage gradients: 0.125%, 1.25%, 2.5%, 5%, and 10% By Weight of Water (BWOW). The corrosion inhibitor dosage was fixed at 2%. Acid and inhibitor dosages were calculated based on the mass of water in the spacer fluid.

The specific procedure was as follows: The spacer fluid was preheated and pre-hydrated for 30 min. A certain volume of pre-hydrated spacer fluid was taken, and the pre-mixed acid and inhibitor solution was added. Then, a certain volume of cement slurry preheated to 90°C was added and mixed uniformly using a spatula. Finally, the rheological properties of the mixture were tested. Rheological compatibility was evaluated using the R-value method.

### *2.4 Spacer Fluid and Cement Slurry Thickening Time Compatibility Test*

To evaluate the impact of residual acid on the thickening compatibility between spacer fluid and cement slurry, tests were conducted using a high-temperature high-pressure (HTHP) consistometer in accordance with American Petroleum Institute (API) Recommended Practice (RP) 10B-2. Two test conditions were applied: 80°C/46.5 MPa and 150°C/94.4 MPa, representing moderate and high downhole temperature–pressure environments, respectively. Two volume ratios of spacer fluid to cement slurry were set: 5/95 and 25/75. Two acid concentrations (50% and 25%) were selected, with five acid dosage gradients: 0.125%, 1.25%, 2.5%, 5%, and 10% BWOW. The corrosion inhibitor dosage was fixed at 2%. Acid and inhibitor dosages were calculated based on the mass of water in the spacer fluid. The thickening time was defined as the time required for the slurry consistency to reach 100 Bearden units of consistency (Bc).

## 3 Results and Discussion

### *3.1 Acid Effect on Spacer Fluid Flushing Efficiency*

Effective flushing of the drilling fluid filter cake by the spacer fluid is key to ensuring the bonding quality of the second interface in cementing. In this study, the "pre-cementing acidification" condition was simulated, i.e., the filter cake was first soaked in acid and then flushed with spacer fluid. This was compared with conventional flushing without acid soaking.

Experimental data shows that the efficiency of conventional spacer fluid flushing after 30 min was 82.61%. However, after soaking the filter cake in 50% concentration stock acid solution (containing 2% corrosion inhibitor) for 2 h, the flushing efficiency under the same procedure increased significantly to 91.90%, an increase of 9.29 percentage points [12–14] (as listed in Table 1).

**Table 1:** Parameters and results of spacer fluid flushing efficiency tests before and after acid soaking.

| $m_1$/g | $m_{2,10min}$/g | $m_{2,15min}$/g | $m_{2,20min}$/g | $m_{2,30min}$/g | $m_3$/g | Flushing Efficiency |
|---|---|---|---|---|---|---|
| 10.5 | 3.25 | 2.91 | 2.85 | 2.71 | 1.07 | 82.61% |
| 9.72 | 2.86 | 2.31 | 2.03 | 1.78 | 1.08 | 91.90% |

This significant improvement is likely attributed to a dual mechanism of chemical dissolution and physical modification:

1. Chemical Dissolution: $H^+$ in the acid reacts vigorously with calcium carbonate (calcareous formation detritus) in the filter cake, generating water-soluble calcium salts and carbon dioxide gas. The micropores generated by the reaction (generating acid-etched micropores and enhancing porosity) destroy the dense structure of the filter cake, significantly reducing its structural strength and adhesion.
2. Surface Modification: Acid soaking may alter the wettability of the filter cake surface, making it easier to be wetted and peeled off by the water-based spacer fluid.

To further investigate the influence of acid dosage and corrosion inhibitor on flushing efficiency, specific volumes of acid were mixed into the spacer fluid to prepare an acid-mixed spacer fluid. Subsequently, the flushing efficiency of this acid-mixed spacer fluid was evaluated under various conditions. Two key trends were identified:

First, in the control group without corrosion inhibitor, as the acid dosage increased, the flushing efficiency showed a downward trend. This may be because the pure strong acid environment caused acid-induced flocculation or cross-linking of some polymer additives (such as fluid loss agents) in the filter cake. Further observation of the appearance of the filter cake after soaking helps to reveal the mechanism of efficiency improvement. The filter cake surface after acid etching showed extensive micro-channeling and porosity enhancement [15,16], losing its overall dense structure, becoming loose and porous, and accompanied by the detachment of large pieces of solid matter. This indicates that the high-concentration acid effectively dissolved the soluble calcium salts (such as calcium carbonate weighting agents) in the filter cake, destroying its structural skeleton. In this state, the hydraulic shear force during subsequent spacer fluid flushing can easily overcome the adhesive force of the filter cake, resulting in a "peeling" cleaning effect. However, when 2% corrosion inhibitor was added, the trend reversed: flushing efficiency at high acid dosages was significantly better than at low dosages. This indicates that the surfactant components compounded in the corrosion inhibitor played a key role in wettability reversal and penetration in the acidic environment [17], counteracting the negative impact of polymer acid-induced flocculation and synergistically improving the cleaning effect. Additionally, because the corrosion inhibitor contains surfactant components that alter surface energy, the improvement in flushing efficiency is a synergistic result of both chemical dissolution by the acid and the wetting enhancement by the surfactant, as evidenced by the lower flushing efficiency in the control group without the inhibitor. The detailed flushing efficiency curves under 50% acid concentration are illustrated in Fig. 1.

Second, comparing three acid concentrations of 50%, 25%, and 10%, the high-concentration acid (50%) had the best flushing effect. This directly corroborates the positive correlation between chemical reaction rate and reactant concentration—high-concentration acid can destroy the filter cake skeleton faster and more thoroughly. Although acid etching can increase formation roughness, it is also possible that excessive acid exposure could weaken the rock matrix at the interface or leave unstable debris, which could negatively impact cement bonding. This highlights the necessity of future mechanical bonding tests. The flushing efficiency results for 25% and 10% acid concentrations are shown in Fig. 2 and Fig. 3, respectively.

### *3.2 Influence of Acid on Rheological Compatibility between Spacer Fluid and Cement Slurry*

If thickening or gelation (i.e., rheological incompatibility) occurs during the contact and mixing of spacer fluid and cement slurry, it will lead to an increase in displacement pressure, which may cause loss of pumpability or channeling in the annulus in severe cases [18,19]. This section systematically investigated the rheological compatibility after mixing with different concentrations and dosages of acid using the R-value

method, a widely adopted approach in the oilfield cementing industry for quantifying fluid incompatibility. The larger the R-value, the stronger the incompatibility; if the R-value is close to 0 or negative, it indicates good compatibility.

Experimental results show that when the spacer fluid is mixed with corrosion-resistant self-healing cement slurry, it exhibits characteristics of mild incompatibility (see Tables 2 and 3). This is usually due to the cross-linking reaction between polymer additives in the spacer fluid and calcium ions or the high alkaline environment in the cement slurry, forming a local network structure.

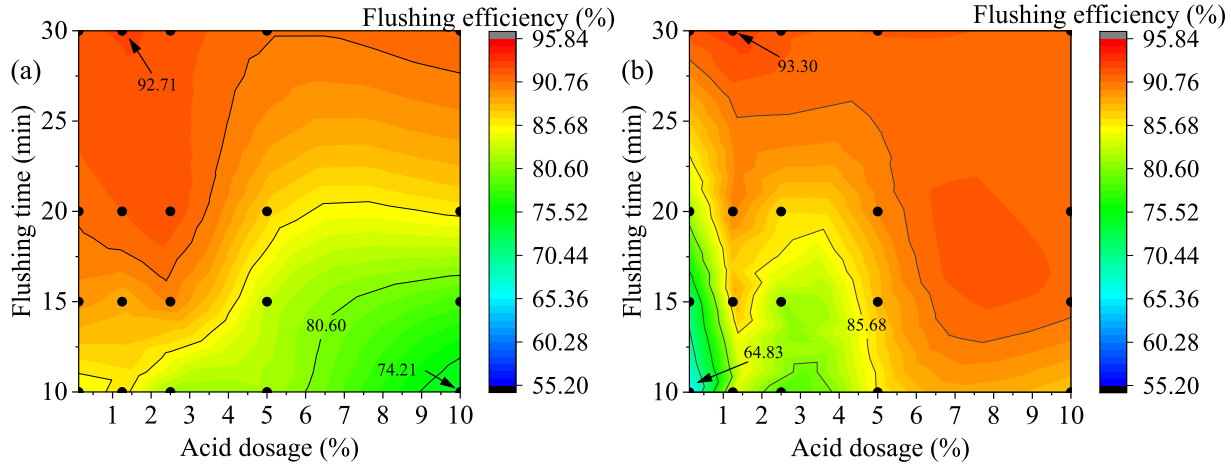


**Figure 1:** Flushing efficiency of the spacer fluid at 50% acid concentration under different acid dosages and flushing times: (**a**) 0% corrosion inhibitor, (**b**) 2% corrosion inhibitor.

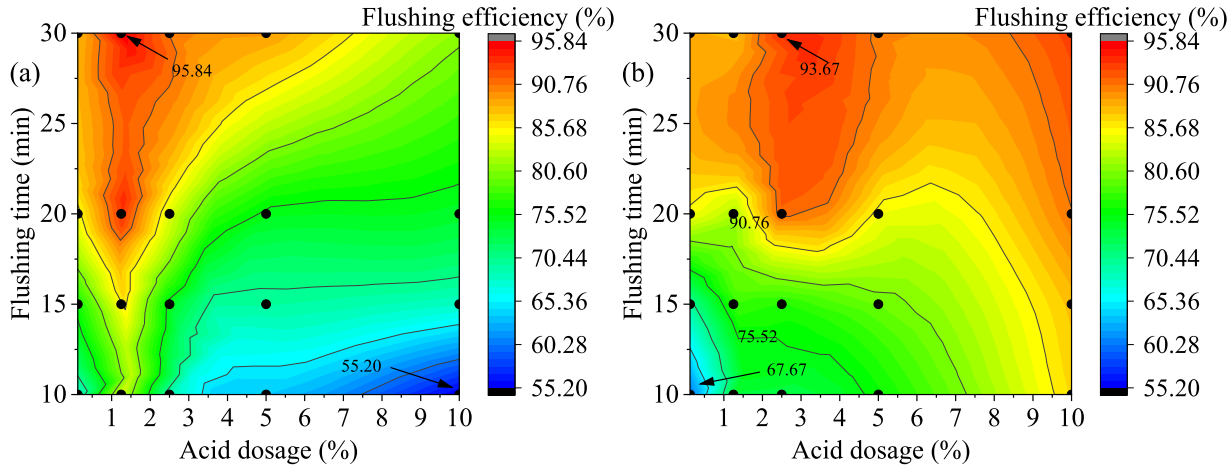


**Figure 2:** Flushing efficiency of the spacer fluid at 25% acid concentration under different acid dosages and flushing times: (**a**) 0% corrosion inhibitor, (**b**) 2% corrosion inhibitor.

However, after the introduction of acid, rheological compatibility was significantly improved, with the following specific laws:

1. Positive Effect of Acid Dosage: As the acid dosage mixed into the spacer fluid increased (from 0.125% to 10% BWOW), the R-value of the mixed fluid showed a significant downward trend. This indicates that the introduction of acid did not trigger the expected “acid-induced flocculation” risk, but instead presumably inhibited alkali-induced polymer cross-linking or hydration swelling by lowering the pH

of the mixed system, thereby disrupting the thixotropic structure and potentially acting as a diluent or gel breaker.

2. Effect of Acid Concentration: Comparing 50% and 25% acid concentrations, high-concentration (50%) acid had a more significant effect on reducing the R-value at the same dosage (R-value dropped to a minimum of 10 at 50% concentration, while the minimum was 17 at 25% concentration, as summarized in Table 3). This suggests that higher $H^+$ concentration or ionic strength may be more conducive to shielding the electrostatic repulsion between polymer chains or destroying the flocculated structure, tending to stabilize the fluidity of the mixed fluid.

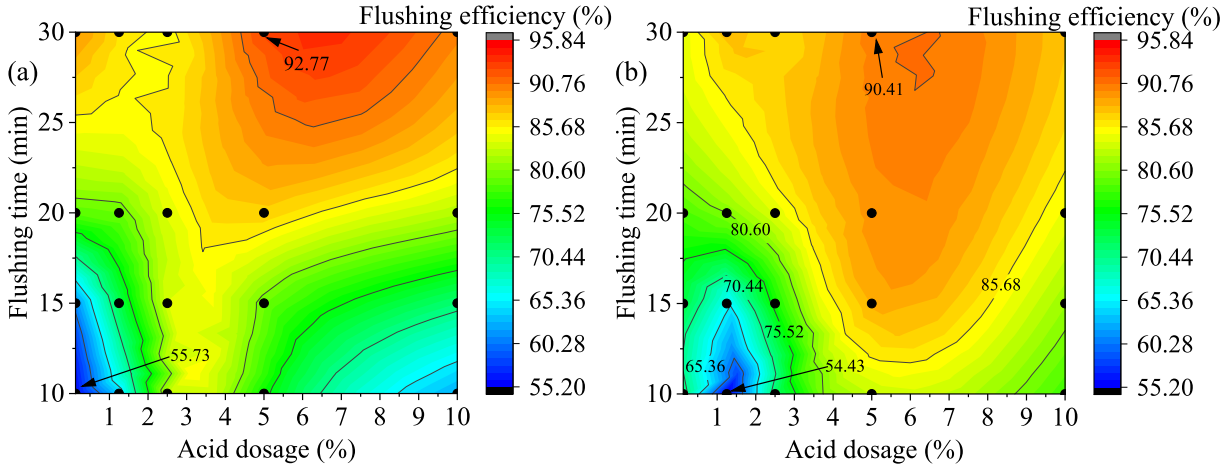


**Figure 3:** Flushing efficiency of the spacer fluid at 10% acid concentration under different acid dosages and flushing times: (**a**) 0% corrosion inhibitor, (**b**) 2% corrosion inhibitor.

It is worth noting that the decrease in R-value upon acid addition might be partly due to the acid thinning or breaking down the spacer fluid polymers rather than a chemical improvement in compatibility. However, from an engineering standpoint, this reduction in mixed fluid viscosity is beneficial as it prevents unexpected gelation or pressure spikes during fluid displacement. In summary, in the "pre-cementing acidification" process, under tested conditions, the presence of residual acid actually helps to alleviate the contact incompatibility between spacer fluid and cement slurry, which is beneficial for reducing displacement resistance and improving displacement efficiency.

**Table 2:** Rheological readings of spacer fluid and cement slurry.

| Fluids | $\phi$ 600 | $\phi$ 300 | $\phi$ 200 | $\phi$ 100 | $\phi$ 6 | $\phi$ 3 |
|---|---|---|---|---|---|---|
| Spacer Fluid | 70 | 52 | 44 | 32 | 8 | 6 |
| Cement Slurry | 225 | 136 | 104 | 60 | 7 | 5 |

### *3.3 Impact of Acid on Thickening Time Compatibility and Safety Evaluation*

Thickening time is directly related to the safety window of cementing operations. In the "pre-cementing acidification" mode, the most concerning risk is the "Flash Set" phenomenon that may be induced after acidic fluid mixes with alkaline cement slurry, where the violent exothermic neutralization reaction causes the cement slurry to instantly lose fluidity. To verify this safety, this experiment simulated the harshest contact conditions at two temperatures: 80°C and 150°C.

### *3.3.1 Thickening Compatibility at 80°C/46.5 MPa*

The thickening time of cement slurry under this condition was 273 min. When mixed with different proportions of the spacer fluid (containing different concentrations of acid and corrosion inhibitor), the test results showed that the thickening times of all mixed slurries exceeded 294 min, and some high acid dosage groups even exceeded 12 h (>720 min), as detailed in Table 4 (50% acid concentration) and Table 5 (25% acid concentration).

**Table 3:** Effect of acid concentration and dosage on the R-value of the mixed fluid.

| Acid Dosage | R-Value | |
|---|---|---|
| (BWOW) | 50% Acid | 25% Acid |
| 0.125% | 21 | 23 |
| 1.25% | 14 | 18 |
| 2.5% | 10 | 18 |
| 5% | 10 | 17 |
| 10% | 10 | 17 |

This result indicates that at this temperature, the acid and corrosion inhibitor system exhibits a strong retarding effect on the cement slurry rather than accelerating setting. The mechanism mainly lies in: organic components in the corrosion inhibitor adsorbed on the surface of cement particles, hindering the hydration reaction; simultaneously, the presence of acid consumes part of the $Ca(OH)_2$ used for early nucleation of hydration, delaying the formation of calcium silicate hydrate (C-S-H) gel. Therefore, under 80°C conditions, the mixed fluid has no risk of flash setting. While the retarding effect prevents flash setting and ensures a safe pumping window, excessive retardation due to high acid concentrations could potentially delay early strength development of the cement. Thus, the dosage of residual acid should be carefully managed in the field to balance pumpability and early set strength.

**Table 4:** Thickening time of mixed fluid at 80°C/46.5 MPa under different volume ratios and acid dosages (50% acid concentration).

| Volume Ratio | Thickening Time/min | | | | |
|---|---|---|---|---|---|
| *v*/*v* | 0.125% | 1.25% | 2.5% | 5% | 10% |
| 5:95 | 302 | 332 | 304 | 337 | 502 |
| 25:75 | 383 | 456 | 640 | >720 | >720 |

**Table 5:** Thickening time of mixed fluid at 80°C/46.5 MPa under different volume ratios and acid dosages (25% acid concentration).

| Volume Ratio | Thickening Time/min | | | | |
|---|---|---|---|---|---|
| *v*/*v* | 0.125% | 1.25% | 2.5% | 5% | 10% |
| 5:95 | 294 | 331 | 332 | 335 | 367 |
| 25:75 | 524 | 521 | 578 | 693 | >720 |

### *3.3.2 Thickening Compatibility at 150°C/94.4 MPa*

High-temperature environments usually accelerate cement hydration and increase the risk of flash setting [20,21]. Experimental results show:

- Low Mixing Ratio (5:95): When a small amount of spacer fluid (mixed with acid) invades the cement slurry, the thickening time of the mixed slurry is basically consistent with that of pure cement slurry (229 min). For example, at 50% acid concentration and 2.5% dosage, the thickening time shortened slightly by 20 min to 209 min, but this is still within the safe construction range, with no drastic rapid thickening inflection point observed (see Table 6).
- High Mixing Ratio (25:75): When the mixing ratio increases, the mixed slurry shows significant retarding characteristics, with thickening times generally longer than 229 min, as detailed in Table 7 (25% acid concentration).

This shows that even at a high temperature of 150°C, the chemical compatibility of this acidification-cementing fluid system remains good. The invasion of acid mainly manifests as "inert" or "retarding" interference, rather than a destructive "strong thermal reaction." This characteristic ensures that when acid channeling or mixing with cement slurry occurs downhole, no solid plug will form in the annulus, indicating fluid compatibility in terms of thickening behavior under these conditions, though comprehensive cementing safety must also account for mud displacement, cement hydration, and mechanical integrity. Furthermore, since the self-healing agent is embedded inside the highly alkaline cement matrix, and any residual acid is quickly neutralized during cement hydration, the transient residual acid exposure does not adversely affect the activation and swelling properties of the self-healing agent, ensuring the long-term integrity of the set cement.

**Table 6:** Thickening time of mixed fluid at 150°C/94.4 MPa under different volume ratios and acid dosages (50% acid concentration).

| Volume Ratio | Thickening Time/min | | | | |
|---|---|---|---|---|---|
| *v*/*v* | 0.125% | 1.25% | 2.5% | 5% | 10% |
| 5:95 | 225 | 211 | 209 | 222 | 236 |
| 25:75 | 248 | 294 | 301 | 348 | 517 |

**Table 7:** Thickening time of mixed fluid at 150°C/94.4 MPa under different volume ratios and acid dosages (25% acid concentration).

| Volume Ratio | Thickening Time/min | | | | |
|---|---|---|---|---|---|
| *v*/*v* | 0.125% | 1.25% | 2.5% | 5% | 10% |
| 5:95 | 230 | 230 | 228 | 216 | 246 |
| 25:75 | 329 | 321 | 343 | 358 | 341 |

### *3.4 Limitations of the Study*

While this study provides valuable insights into the compatibility of cementing fluids and residual acid, several limitations should be noted. First, fresh hydrochloric acid solutions were used to simulate residual acid, whereas downhole residual acid is typically partially spent and contains complex reaction products (e.g., calcium and magnesium ions) that may further influence fluid chemistry. Second, the laboratory tests were conducted under simplified static or rotational conditions, which do not fully replicate the dynamic placement and mixing behaviors in complex annular geometries. Lastly, this work focused exclusively on fluid compatibility (rheology and thickening time) and did not evaluate the mechanical properties, bonding strength, or long-term durability of the set cement sheath in contact with acid-exposed formations.

Future research incorporating spent acid systems and mechanical shear testing is recommended to address these aspects.

## 4 Conclusions

1. Pre-soaking the drilling fluid filter cake with a 50% concentration acid solution enhances the flushing efficiency of the spacer fluid from 82.61% to 91.90%, driven by the dual mechanisms of chemical dissolution and surface modification. The addition of a corrosion inhibitor is critical in modifying surface wettability, thereby facilitating filter cake removal under higher acid dosages.
2. The introduction of residual acid effectively mitigates the contact-induced thickening (signified by a reduced compatibility index, or R-value) between the spacer fluid and the cement slurry. This is achieved by lowering the pH of the system and disrupting the cross-linked polymer networks. Higher acid concentrations exhibit a more pronounced effect in improving rheological compatibility.
3. Over the temperature range of 80°C to 150°C, the mixed fluids exhibit no risk of flash setting across all tested acid concentrations and mixing ratios, with thickening times consistently meeting operational safety requirements. Under high-temperature conditions, a minor influx of residual acid has a negligible impact on cement hydration, whereas larger acid volumes introduce a manageable retarding effect, thereby validating the chemical compatibility of the pre-cementing acidification process at the fluid level.

**Acknowledgement:** Not applicable.

**Funding Statement:** The authors received no specific funding for this study.

**Author Contributions:** The authors confirm contribution to the paper as follows: conceptualization, Wei Wang and Hao Guo; methodology, Cheng Jian and Yi Yu; investigation, Wei Wang, Hao Guo, Cheng Jian, Yi Yu and Quanmin Jiang; data curation, Quanmin Jiang; writing—original draft preparation, Wei Wang; writing—review and editing, Chunyu Wang; supervision, Chunyu Wang. All authors reviewed and approved the final version of the manuscript.

**Availability of Data and Materials:** The authors confirm that the data supporting the findings of this study are available within the article.

**Ethics Approval:** Not applicable.

**Conflicts of Interest:** Authors Wei Wang, Hao Guo, Cheng Jian, Yi Yu, and Quanmin Jiang are employees of CNOOC China Limited, Zhanjiang Branch. The authors declare no other potential conflicts of interest.

## References

1. Gao Y, Lian S, Shi Y, Yang X, Zhou F, Xiong C, et al. A new acid Fracturing fluid system for high temperature deep well Carbonate reservoir. In: Proceedings of the SPE Asia Pacific Hydraulic Fracturing Conference; 2016 Aug 24–26; Beijing, China. [CrossRef]
2. Geng Y, Zhou J. Parameter optimization of acid fracturing in ultra-deep fault zone carbonate reservoir. E3S Web Conf. 2022;338:01021. [CrossRef]
3. Molenaar MM, Singhal NK, Brady ME, Vitthal S, O'Brien CG. Acid Fracturing and hydraulic Fracturing applied in a single well for a deep Carbonate reservoir appraisal. In: Proceedings of the SPE International Hydraulic Fracturing Technology Conference and Exhibition; 2025 Sep 23–25; Muscat, Oman. [CrossRef]
4. Wu X, Hill AD, Oeth C, Zhu D, Gildin E. Integrated 3D acid Fracturing model for Carbonate reservoir Stimulation. In: Proceedings of the OTC Brasil; 2013 Oct 29–31; Rio de Janeiro, Brazil. [CrossRef]

5. Li X, Zhao Z, Ma X, Wang X, Zhou H. Case studies of tight-gas Carbonate reservoir Stimulation: acid Fracturing vs. Propped Fracturing. In: Proceedings of the SPE Annual Technical Conference and Exhibition; 2006 Sep 24–27; San Antonio, TX, USA. [CrossRef]
6. Kudrashou VY, Nasr-El-Din HA. Formation damage and compatibility issues associated with use of Corrosion Inhibitors in well Acidizing—a review. In: Proceedings of the SPE/ICoTA Well Intervention Conference and Exhibition; 2019 Mar 26–27; The Woodlands, TX, USA. [CrossRef]
7. Du J, Shu H, Shi Y, Zou Q, Liu P, Liu J, et al. Experimental investigation of acid-rock reaction kinetics and fracture conductivity under ultra-high temperature carbonate reservoir conditions. SSRN Electron J. 2024. [CrossRef]
8. Aghajafari AH, Shadizadeh SR, Shahbazi K, Tabandehjou H. Kinetic modeling of cement slurry synthesized with Henna extract in oil well acidizing treatments. Petroleum. 2016;2(2):196–207. [CrossRef]
9. Salimi A, Beni AH, Bazvand M. Evaluation of a water-based spacer fluid with additives for mud removal in well cementing operations. Heliyon. 2024;10(4):e25638. [CrossRef]
10. Alkhalaf S, Al-Yami A, Wagle V, Al-Safran A. Development of new Inhibited Spacer for cementing operation. In: Proceedings of the Volume 10: Petroleum Technology; 2022 Jun 5–10; Hamburg, Germany. [CrossRef]
11. American Petroleum Institute (API). API specification 10A: specification for cements and materials for well cementing. 25th ed. Washington, DC, USA: API Publishing Services; 2019.
12. Elkatatny SM, Nasr-El-Din HA. Removal efficiency of water-based drill-in fluid filter cake using Polylactic acid. In: Proceedings of the SPE Europec/EAGE Annual Conference; 2012 Jun 4–7; Copenhagen, Denmark. [CrossRef]
13. Carpenter C. Enzyme-based cleanup fluid effective for high-temperature filter-cake removal. J Petrol Technol. 2024;76(3):83–5. [CrossRef]
14. Mahadi KA, Nizam MI, Jadid MB, Ogbonna C, Hashim S, Chen YC. Use of acid precursor as alternative to acid treatment to drill-in fluid filter cake removal: FN case study. In: Proceedings of the International Petroleum Technology Conference; 2014 Dec 10–12; Kuala Lumpur, Malaysia. [CrossRef]
15. Cheng H, Zhu D, Hill AD. The effect of Evolved CO2 on Wormhole Propagation in Carbonate Acidizing. In: Proceedings of the SPE International Conference and Exhibition on Formation Damage Control; 2016 Feb 24–26; Lafayette, LA, USA. [CrossRef]
16. Wang F, Tan Y, Zhou F. Experimental investigation of Wormhole Propagation during alternative Acidizing in Carbonate reservoirs. Arab J Sci Eng. 2025;50(13):10259–68. [CrossRef]
17. Shi Y, Niu F, Mohanty K. Wettability Alteration with weak acid assisted Surfactant flood. In: Proceedings of the SPE Annual Technical Conference and Exhibition; 2022 Oct 3–5; Houston, TX, USA. [CrossRef]
18. Cadix A, Molinie V, Wilson J. Effect of fluid loss polymers architecture on cement Slurry Rheology: impact of adsorption and Microstructure. In: Proceedings of the SPE International Conference on Oilfield Chemistry; 2019 Apr 8–9; Galveston, TX, USA. [CrossRef]
19. Shadravan A, Tarrahi M, Amani M. Intelligent tool to design drilling, spacer, cement slurry, and fracturing fluids by use of machine-learning algorithms. SPE Drill Complet. 2017;32(2):131–40. [CrossRef]
20. Ali W, Al-Turki FA, Lopez F, Bouaraki M. Modified testing protocol to determine the precise Thickening time of cement Slurry: A field-centered approach to prevent the Premature setting of cement Slurry while placement and maximizing the operational efficiency. In: Proceedings of the Gas & Oil Technology Showcase and Conference; 2023 Mar 13–15; Dubai, United Arab Emirates. [CrossRef]
21. Wang C, Wang L, Yao X, Du J, Zhai W, Guo S, et al. The effect of rutin on the early-age hydration of oil well cement at varying temperatures. Cem Concr Compos. 2022;128:104438. [CrossRef]