Fuel 217 (2018) 444–457

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

An experimental and numerical study of wellbore leakage mitigation using pH-triggered polymer gelant

Shayan Tavassoli*, Jostine Fei Ho, Mohammadreza Shafiei, Chun Huh, Paul Bommer, Steven Bryant[1], Matthew T. Balhoff

The University of Texas at Austin, United States

A R T I C L E I N F O

Keywords:
pH-triggered polymer gel
Carbon storage
Wellbore leakage mitigation

A B S T R A C T

The potential leakage of hydrocarbon fluids or carbon dioxide from subsurface formations is a primary concern in wellbore integrity, oil and gas production, and CO_2 storage. Leaky wells with fractured cement or debonded microannuli are common sources of subsurface fluid leakage. The hydrocarbon fluid or CO_2 can migrate through such pathways to shallower formations and ultimately to surface. Cement fractures may have apertures on the order of microns, which are difficult to seal with typical workover techniques.

A material that provides low viscosity during the injection but much higher viscosity after injection, with a minimum pressure gradient to yield flow at the target zone, is a potentially effective approach to seal the leakage pathways through cement fractures. pH-triggered polymers are such a material: aqueous solutions with low viscosity at low pH, containing pH-sensitive microgels which viscosify upon neutralization to become highly swollen gels with substantial yield stress that can block fluid flow. For the wellbore leakage application, the large alkalinity of wellbore cement provides the required neutralization. Our coreflood and rheological experiments show that pH-triggered polymer sealants such as polyacrylic acid polymer provide a robust seal if the process is properly designed; however, its long-term applicability depends on the dynamic geochemical environment of the wellbore. The process comprises three stages: (1) injection of a chelating agent as the preflush to ensure a favorable environment for the polymer gel, (2) injection of polymer solution, and (3) shut-in for the polymer gelation. A systematic study was done to understand the conditions under which the polymer gel remains stable and effectively seals the leakage pathways.

A numerical model, based on polymer rheological properties and governing mechanisms observed in the laboratory experiments, was developed to simulate the reactive flow and transport of pH-triggered polymers in narrow fractures. Comparison with experiments shows a generally good agreement, despite the relative simplicity of the model. The numerical model was used to investigate further the underlying mechanisms of the process. The results can be used to design effectively the remediation process for a known fracture aperture size of the target zone.

1. Introduction

Wellbore integrity is one of the most important concerns in the oil and gas industry and geological storage of CO_2. It is the ability of the wellbore cement to maintain zonal isolation in geological formations. Wellbore integrity problems can be found in many existing wells and a common cause is a poor cement job. If the integrity of the wellbore is compromised (wellbore integrity failure), pressurized formation fluids can migrate through leakage pathways to other strata and ultimately to the surface. Leakage pathways in the wellbore cement can be caused by either mechanical well failures (e.g. from cyclic pressure and temperature changes), or chemical degradation from formation fluids [1]. Wellbore integrity failure might cause economic loss, environmental contamination, and/or endanger the safety and success of the project.

Carbon dioxide capture and storage (CCS) is aimed to sustainably mitigate CO_2 content in the atmosphere. The CCS technology comprises three steps: (1) capture of CO_2 from power plants or industrial processes, (2) transport of captured and compressed CO_2, and (3) geological storage of CO_2 in subsurface formations [2]. The long-term containment of CO_2 is crucial to the success of this technology. Several trapping mechanisms such as structural and stratigraphic, capillary,

* Corresponding author.
E-mail address: s.tavassoli@utexas.edu (S. Tavassoli).
[1] Now at University of Calgary.

https://doi.org/10.1016/j.fuel.2017.12.098
Received 18 July 2017; Received in revised form 6 December 2017; Accepted 22 December 2017

Nomenclature

B	effective hydraulic aperture, L
c	species concentration
D	diffusion coefficient, $L^2\,t^{-1}$
g	gravitational constant, $L\,t^{-2}$
K	consistency index, $m\,L^{-1}\,t^{n-2}$
L	length, L
m	exponent in the Herschel-Bulkley-Papanastasiou model, t
n	power-law index
k_B	Boltzmann's constant, 1.38064852E − 23 ($m^2\,kg\,s^{-2}\,K^{-1}$)
Q	volumetric flow rate, $L^3\,t^{-1}$
R	chemical reaction rate, t^{-1}
R_h	hydrodynamic radius of chemical species, L
r_H	hydraulic radius, L
t	time, t
T	temperature, T
$\boldsymbol{u}$	velocity vector, $L\,t^{-1}$
W	width, L
P	pressure, $m\,L^{-1}\,t^{-2}$
$\dot{\gamma}$	shear rate, t^{-1}
μ	viscosity, $m\,L^{-1}\,t^{-1}$
η	apparent viscosity, $m\,L^{-1}\,t^{-1}$
ρ	density, $m\,L^{-3}$
σ	shear stress, $m\,L^{-1}\,t^{-2}$
σ_y	yield stress, $m\,L^{-1}\,t^{-2}$

SI Metric Conversion Factors

cp × 1.0 E − 03 Pa.s
ft × 3.048 E − 01 m
psi × 6.894757 E + 03 Pa

solubilization, and mineralization contribute to the long-term containment of CO_2 [3]. The potential for leakage will depend on wellbore integrity, cap rock seal integrity, and various trapping mechanisms [4]. The detection and characterization of CO_2 leakage can be accomplished by different methods such as interpretation of seismic data, pressure pulse testing, gravity, electrical resistivity tomography, etc. [5–12]. CO_2 plumes can potentially leak through the fractures developed in the cement or debonded microannuli formed between cement and surrounding materials [13]. Therefore, an efficient method is needed to seal the potential leakage pathways and improve the project sustainability in terms of CO_2 entrapment and safety.

Several methods have been introduced in the literature and used in field operations to repair poor cement jobs and seal potential leakage pathways. Squeeze cementing is a typical practice in which cement slurry is pushed to the leakage zone to fill and plug the potential gaps [14–17]. However, squeeze cementing is not very efficient for repairing small fracture conduits (less than 400 μm) as solids in the cement slurry can be screened out from dispersing fluid and cannot enter the remaining smaller fractures [18,19]. In addition, bridging and cement dehydration will occur when the slurry is squeezed to penetrate narrow fractures [20]. Alternative technologies include ultra-fine cement (e.g. Halliburton's Micro Matrix®, Schlumberger's SqueezeCRETE®, etc.), in which smaller particles are used in the cement slurry to improve its penetration capability through smaller fractures, as well as application of solid-particle-free sealants (e.g. Halliburton's Injectrol® and Permseal®, Nalco's BrightWater®, etc.) in which the screen-out effect of solid particles has been eliminated. The sealant can be a gel or a polymer solution that viscosifies upon a triggering process such as contact to specific ions or solid surface, reach to a specific depth or temperature, biomineralization, hardening, polymerization and cross linking, etc. There are some limitations associated to these sealants due to the triggering mechanism, temperature tolerance, thickening reaction time, environmental compatibility, strength to block the penetrating fluid, etc. [21–23].

The pH-triggered polymer gelant described in this work is a specific type of sealant in which the triggering mechanism is an increase in alkalinity (pH). This gelant is an aqueous solution of polyacrylic acid microgels (trade name Carbopol®) that swell and viscosify as the pH of the environment increases [24]. The polymer gelant is initially water-like at the pH of injection and it turns into a viscous polymer gel as pH increases in contact with alkaline cement. Low viscosity during the injection assures favorable injectivity and thorough penetration to the target zone. The hydrated cement, mainly as calcium hydroxide, is highly alkaline that has sufficient neutralization capacity to trigger the pH transition for gel formation. The polymer gel viscosity can increase several orders of magnitude upon this neutralization and its value depends strongly on polymer concentration, pH, and salinity [25–28].

The long-term applicability of the gel depends on the dynamic geochemical environment of the wellbore. Many studies have been conducted to better understand and characterize this dynamic behavior [29–31]. High alkalinity of cement, pH of about 13 [32], might negatively impact the durability of the pH-triggered polymer gel. However, this effect is partially inhibited by the formation of a deposit layer on the cement surface, which will be discussed. Application of polyacrylic acid polymer to seal cement fractures in the wellbore is economically affordable and can be repeated, if necessary. Its application provides a temporary or long-term remedy depending on the dynamic geochemical environment of the wellbore; however, a permanent approach such as well plugging and abandonment [23] might be needed considering the safety guidelines and regulations, and the viability of the well.

The advantages of using the pH-triggered polymer gelant are convenience in its application without the need of additives and polymer cross-linkers, affordability, commercial availability, use of well-known environmentally friendly materials, and ease of injection. Last but not least, pH-triggered polymer gelants provide an efficient sealing in very narrow fractures because of the direct correlation of polymer gel strength and the reciprocal of fracture aperture size. Therefore, pH-triggered polymers can be a potential remedy to wellbore leakage where other common methods such as squeeze cementing are not efficient.

In this paper, we investigate the application of the pH-triggered polymer gel to seal cement fractures and its underlying mechanisms.

2. Methodology

2.1. Rheology measurements

The pH-triggered polymer gel sealant is an aqueous solution of polyacrylic acid hydrogel particles. The polymer gel swells and adsorbs water as pH increases. Fig. 1 shows the polyacrilic acid molecular

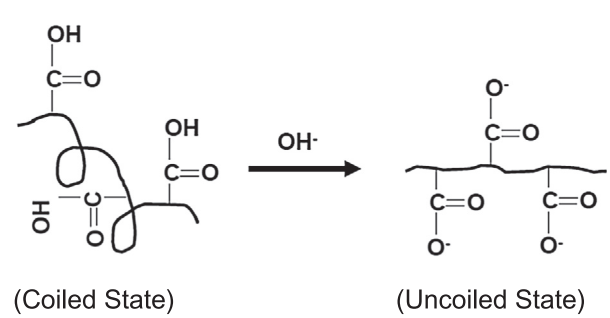

Fig. 1. Polyacrylic acid structure and its state transition (coiled to uncoiled) upon ionization [25].