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Pilot size process visualization: Gravity fluid displacement method to stop annular gas migration

Efecan Demirci [a,*], Andrew K. Wojtanowicz [b]

[a] Turkish Petroleum Corporation, Kirklareli, Turkey
[b] Louisiana State University, Baton Rouge, USA

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ABSTRACT

Irreducible casing pressure, also known as Sustained Casing Pressure (SCP), cannot be bled off as it is caused by late gas migration in the annular fluid column above the top of leaking cement. The leaking cement problem is widely spread as shown in statistics from Gulf of Mexico, Canada, Norway and other places where SCP has been regulated. The regulations require removal of severe SCP to continue well's operation and removal of any SCP prior to well's plugging and abandonment (P&A).

Typically, SCP removal requires either downhole intervention or annular intervention methods. The latter method involves displacing the annular fluid above the top of the gas-leaking well cement with a heavy fluid to increase the hydrostatic pressure and stop the gas leak. Past field applications of the method failed – most likely due to incompatibility of the two fluids. In this study, a see-through scaled-down hydraulic analog of the well's annulus was designed based on a population of typical annulus sizes and used for video-taped displacement experiments with clear synthetic-clay muds and heavy (kill) fluids.

The results show that miscible combination of the two fluids mix at the contact and show poor displacement. However, immiscible hydrophobic kill fluids settle rapidly in the annular fluid and provide more effective displacement. The study demonstrates importance of controlled injection of the kill fluid by adjusting the rate and nozzle size to set out efficient buoyant settling and prevent initial dispersion. The results also show that horizontal injection is superior to vertical injection as the impingement effect increases the efficiency of the displacement process. A side- (versus top-) injection geometry and the injection rate data are analyzed to develop empirical correlation of maximum injection rate for a given properties of the two fluids.

1. Introduction

Sustained casing pressure (SCP) result from late gas migration in one of the well's annuli and manifests itself at the wellhead as irreducible casing pressure (Bourgoyne et al., 2000). SCP poses environmental risk of gas emissions to the atmosphere (Kinik, 2012) and regulations (Bureau of Safety and Environment Enforcement, BSEE) require removal of SCP – particularly prior to well's plugging and abandonment (P&A) operation. As conventional SCP removal techniques – involving rig intervention – are very expensive, there is a need for improvement.

Less expensive methods than the rig-methods involve injecting "killing" material into the well's annulus to create a barrier against the leaking cement and stop gas migration. Since the only access to the casing annulus is through the valve at the casing-head, the killing material can either be introduced with flexible tubing inserted to certain depth of the annulus (Casing Annulus Remediation System, CARS), or by direct injection to the top valve. Previous applications show that CARS can only reach to 1000 feet depth and was not effective in deeper annuli (Wojtanowicz et al., 2001). Another study involved dropping down a metal into the infected annulus, allowing to accumulate at the top of cement and melting it with an induction-heating tool to create a plug that stops the gas leak (Carpenter et al., 2004). Although the small-scale tests showed promising results on plugging the annular space this technology was never tried in a more realistic multi-annular system and has not been commercialized, yet.

* Corresponding author. TP Bolge Mudurlugu, P.O. 39750, Luleburgaz, Kırklareli, Turkey. Tel.: +90 5356953314.
E-mail addresses: efecandemirci@gmail.com (E. Demirci), awojtan@lsu.edu (A.K. Wojtanowicz).

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In the past, another rig-less technique, Bleed and Lube (B&L), of SCP removal has also been tried. In principle, the method involves replacing the fluid in the affected annulus (annular fluid) with a higher-density fluid (kill fluid) in order to increase the hydrostatic pressure on top of cement and stop gas migration (Nishikawa, 1999). Unlike the other rig-less methods B&L does not require flexible tubing and can be applied to any annulus where a top valve is available. When using miscible combinations of kill and annular fluids (zinc bromide or heavy mud) a few case histories reported some reduction in SCP but an effective displacement has never been accomplished (Wojtanowicz et al., 2001). Previous experimental studies revealed that zinc-bromide caused rapid flocculation of annular fluid that would behave as a plug and prevent kill fluid transport downward (Nishikawa, 1999; Nishikawa et al., 2001). Heavy mud, on the other hand, would mix with annular fluid, dilute and return to the surface during the bleed-off cycle. The study suggested immiscible kill fluid as the essential requirement for an effective displacement process.

All displacement studies, to date, have used physical models with annular geometries. Although, downscaling of any annulus into similar shapes seems realistic, concentric geometry lacks visualization. Non-circular hydraulic has been studied by researchers using equivalent diameter approach, which simply relates any flow geometry to flow pipe (Anifowoshe and Osisanya, 2012; Erge et al., 2014, 2015). However, the approach has not been used for buoyant settling studies. The paper proposes a new physical model design and attempts to qualitatively explain the miscible and immiscible displacement mechanisms, and to quantify efficient displacement.

2. Experimental setup

2.1. Physical model and fabrication

A pilot physical model, dubbed here "slot model", has been designed by converting annular geometry to rectangular geometry (Fig. 1). In order to maintain hydraulic similarity equivalent diameter (d_e) approach has been used (Munson et al., 2009). When hydraulic diameters (or hydraulic radiuses, r_H) of both shapes are equated below relationship (Eq. (3)) is obtained; where, Δd = thickness and w = width of the model.

$$d_e = 4r_H \tag{1}$$

$$r_H = \frac{w\Delta d}{2(w + \Delta d)} \tag{2}$$

$$w = \frac{2r_H \, \Delta d}{\Delta d - 2r_H} \tag{3}$$

A population of 40 typical sizes of oil well annuli from 5 to 13-3/8 inches has been analyzed and hydraulic radii calculated. For statistical analysis hydraulic radii values have been organized into 5 classes with the increments of 0.165 inches. Calculated P10, P90, average and median values are shown in Table 1. As shown in Fig. 2, statistical analysis gives right-skewed distribution with median value 0.65. Fig. 3 shows the plots of the slot model width versus thickness for different central tendency measures of well annuluses. The selected design for the slot model was 1.3 inches thickness, and 20 inches width that was later changed – due to fabrication constraints – to 1.35 and 13.5 inches, respectively.

The slot model was fabricated at Louisiana State University (LSU) using one 0.75 inches thick glass window for the front plate and a chemically-resistant plastic for the back plate. Fluid displacement process in the model could be seen and recorded with a video camera placed in front of the glass window. The model, shown in Fig. 4, features two 0.6-inch injection ports (top and side injection), and two one-inch overflow ports at two top corners of the model, with hoses draining the overflow fluid. Various sizes of nozzles could be installed using a flow manifold with a flowmeter at the top of the model. A Teflon single cavity ½ HP motor pump is used for injecting heavy (kill) fluid. A pressure transducer is installed at the bottom drainage line to read the bottom pressure changes.

2.2. Fluid properties

In the experiments, various immiscible and miscible kill fluids (KF) are used. Immiscible brominated organics have densities between 12 and 17 ppg, viscosities between 8 and 235 cP and interfacial tensions between 21.5 and 32 dyn/cm. Miscible kill fluids are weighted freshwater bentonite drilling muds with barite, or potassium formate-water solutions. Detailed properties of kill fluids are given in Table 2.

Since the clay-based annular fluids are opaque for visual observation, Non-Newtonian translucent fluids (TF) have been formulated using Laponite, a synthetic clay, water, and PAC or

Table 1
Statistical properties of hydraulic radiuses (Demirci and Wojtanowicz, 2015).

Count	40	# of classes	5
Max value	1.181	Class width	0.165
Min value	0.459	Average	0.66
Range	0.722	Median	0.653
P10	0.35	P90	0.82

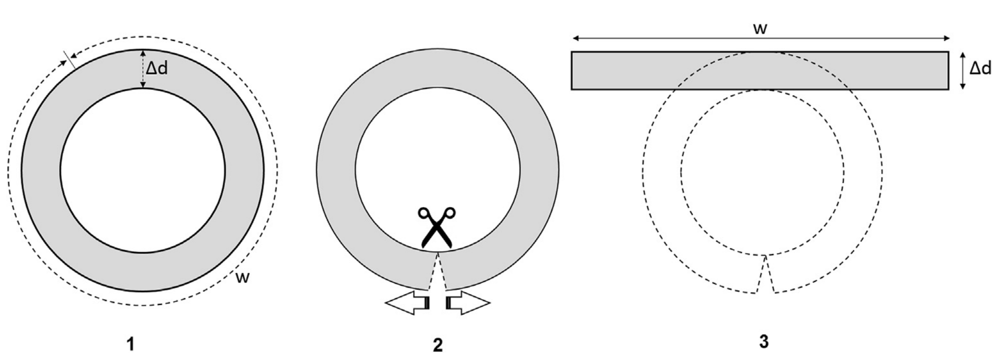

Fig. 1. Conversion of annulus (1) to slot (3).