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Improvement of zonal isolation in horizontal shale gas wells: A data-driven model-based approach

Shyam Panjwani [a], Jessica McDaniel [b], Michael Nikolaou [a, *]

[a] Chemical & Biomolecular Engineering Department, University of Houston, Houston, TX 77204-4004, USA
[b] CSI Technologies LLC, Houston, TX 77073, USA

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ABSTRACT

Shale gas production from horizontal wells may encounter potential problems because of gas leakage from various zones of a well into the air and ground water reserves. Stopping such leaks is a serious challenge faced by the shale gas industry. To stop gas communication between various zones of the well, lifelong integrity of the cemented annulus between the metal casing and the borehole wall must be ensured. Various physical factors i.e. casing properties (internal diameter, centralizers and casing-hole relationship), cement and drilling mud properties (density, viscosity, additives), and other variables, such as temperature and pressure, affect the quality of cement job. The quality of cement job was analyzed in terms of sustained casing pressure. Sustained casing pressure or SCP results from sustained pressure on an annulus seen at surface from fluid or gas leaking from a lower formation as a result of poor zonal isolation. The SCP value was used in categorizing horizontal shale gas wells as leaking or not leaking. The statistical classification model was built to predict whether a well will leak or not, under the effect of various physical factors. The multivariate statistical technique PLS-DA (Partial Least Square Discriminant Analysis) was used to build this model and as the input (predictor) variables, the model used dimensionless groups of the physical factors. The VIP (variable importance in projection) variable selection method was used to identify highly impacting physical factors and the optimal model structure was determined using the 10-fold cross validation method. The model was able to correctly classify 81% of the classified wells in cross-validation tests for intermediate casing. The types of data-driven models developed are helpful in predicting whether annular gas leakage will occur under the influence of physical factors and based on the model feedback, the responsible factors can be regulated to perform better cement job, which would result in reduced gas leakage and less remedial cementing cost.

1. Introduction

Oil and gas production from unconventional reservoirs has transformed the US energy landscape with profound economic and environmental implications. Indeed, the US chemical industry now has the advantage of inexpensive natural gas as a raw material produced domestically; and the power industry is increasingly relying on natural gas, as an alternative to coal, for electricity generation with reduced greenhouse gas and other emissions, higher flexibility and compatibility with renewables, and lower cost (Biello, 2015). However, shale gas production is not without environmental risks. An important consideration is potential gas leakage from various geological zones of a production well, either into the air or into underground water reserves. In fact, undesired gas emissions into the air – in addition to wasting a valuable resource – could potentially cancel any advantages on greenhouse gas emissions reduction stemming from use of natural gas in power generation (Howarth et al., 2012a, b), as methane has more than an order of magnitude higher global warming potential than CO2 (IPCC, 2013). The acceptable threshold of natural gas leaks, above which total greenhouse gas emissions would actually increase, is vigorously debated (Howarth, Ingraffea, et al., 2011), on occasion among scientists within the same institution (Cathles et al., 2012; Howarth, Santoro, et al., 2011; Howarth et al., 2012a,b), and has

* Corresponding author. Chemical & Biomolecular Engineering Department, University of Houston, Houston, TX 77204-4004, USA.
E-mail address: Nikolaou@uh.edu (M. Nikolaou).

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spawned high-profile scientific investigations (Caulton et al., 2014). Nevertheless, developing cost-effective solutions for unwanted natural gas leaks is an opportunity welcome by industry (Boling, 2015).

Preventing the undesired flow of natural gas between various well zones and rock formations is known as zonal isolation, and is achieved by creating a tight seal through cementing appropriate sections of a well. Providing adequate zonal isolation remains formidable for industry, because uniform placement of cement in the annulus between the metal casing and the wellbore formation is both technically challenging and costly. In current industrial practice, predicting zonal isolation mainly relies on laboratory investigations and/or predictions based on analytical models or finite-element analysis. Investigators have reported the effect of internal casing pressure and temperature on zonal isolation in experimental studies (Goodwin and Crook, 1992; Jackson and Murphey, 1993) and the effect of well events, such as completion and production, using finite-element methods (Tahmourpour and Griffith, 2004; Thiercelin et al., 1998). Correlation-based studies of the effect of formation properties on gas migration have also been presented (Wilkins and Free, 1989).

Although such studies are quite useful for individual tasks related to well cementing and zonal isolation, no method has been presented to account for the combined effect of all related factors on the quality of a cement job. Yet such factors interact with one another, and their overall effect can be difficult to anticipate, either using fundamental equations (which become overly unwieldy) or by invoking experience (which, by itself, is insufficient). In particular, cementing operations and design for horizontal wells are generally more demanding than for vertical wells, and routinely require decisions on a large number of factors. Such decisions include cement-slurry design, spacer design, casing design, centralization, and evaluation of a cement job after its completion, among others.

Assessing the effect of all such factors in a systematic way would be helpful for cementing engineers. In fact, a mathematical model that could make reasonable quantitative predictions would help the engineer perform what-if analysis and possibly optimize the cementing operation. Development of a mathematical model based on first principles would be extremely difficult in this case, because of the significant uncertainty and complexity in the fundamental equations governing the cementing process. Alternatively, a data-driven model could be built, provided that sufficient data is available.

A key focus of this work is the development of such a data-driven mathematical model. Input (predictor) variables to this model are factors that generally may have an effect on the quality of a cement job. The output variable of this model is characterization of cementing quality of a well section, through classification of a section as leaking or non-leaking, along with the relative confidence of such a prediction. The model is built using multivariate statistical analysis on data already available from a number of cemented wells; no first-principles equations are employed at all. The model can be used to guide the design of subsequent cement jobs. As additional data is collected, the model can be further refined and provide better predictions. A preliminary version of this work was included in an earlier presentation by the authors (Panjwani and Nikolaou, 2013).

In the rest of the paper, we first present a brief description of factors affecting the quality of cementing, and provide a quick overview of commonly used modeling methods that are relevant to our work. An application of the proposed method is presented next, through a cross-validation study with data from several leaking and non-leaking cemented wells. Based on positive results from this study, conclusions are drawn and recommendations are made in the last section.

2. Background and related literature

2.1. Cement sheath quality

Well cement sheath quality is affected by a number of factors, of which the following are significant.

2.1.1. Casing design

This includes the type of casings used for surface, intermediate, and production zones, internal diameter of casing, casing weight per unit length, number and type of centralizers, and casing/hole diameters ratio. The main purpose of using centralizers is to reduce eccentricity of casing in the borehole. Depending on the eccentricity of casing, a large number of centralizers may be required, but this creates a problem of extra drag while running casing, which is why spacing between centralizers needs to be calculated for minimizing the drag. Casing weight, hole-diameter, and hole-deviation play an important role in determining the minimum standoff (an eccentricity measure of casing pipe placement inside the borehole) required for uniform cement flow in the upper and lower parts of the horizontal section of the annulus. Minimum standoff required is 60% for uniform flow of cement inside the annulus. In general, the size of the annulus lies in a recommended range (0.75–1.5 inch). Casing movement, i.e. rotation or reciprocation, also affects the displacement efficiency as it breaks the agglomeration of gelled drilling mud (Nelson, 1990). Casing-connection is also an important part of casing-design, as they help in resisting leaks from excessive internal or external fluid pressure and provide structural rigidity. There are a few different casing connections, such as round thread and buttress thread. Casing connections may sometimes have a larger outer diameter than the body of the casing. Typically that only happens for the smaller casing sizes.

2.1.2. Rheological properties

Such properties include gel strength, plastic viscosity, and yield point. A number of researchers have suggested use the of drilling muds with ratio of yield point to plastic viscosity greater than one (Zurdo et al., 1986). These properties affect the cement pumpability through the casing pipe and annulus. They also affect the drilling mud displacement by cement during cementing as they help to prevent settling of solids inside the horizontal annulus. It should be stressed that the key to successful cement jobs is the properties of the slurries themselves, regardless of how such properties were achieved.

2.1.3. Cement properties and cementing procedure

The properties of the cement slurry used in the lead and tail systems of a cemented section are generally different. In either case, important variables that ultimately affect cementing quality are slurry type, slurry density, slurry rheological properties, slurry free water content, fluid loss rate, thickening time, compressive strength, Young modulus and cement pumping rate. The use of inadequate slurry might pose well control issues. Since the bottomhole temperature affects cement properties, such as compressive strength development, fluid loss rate, or thickening time, the cement slurry should have adequate properties to avoid any downhole cement integrity problems. The Young modulus of the cement should be more than the Young modulus of the rock to achieve better cement job quality (Thiercelin et al., 1998). The type and volume of a spacer, placed between the cement slurry front and the drilling mud displaced by the cement, play an important role in cementing, as they avert potential problems related to intermixing