Journal of Petroleum Science and Engineering 145 (2016) 66–76

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Relationship between operational variables, fundamental physics and foamed cement properties in lab and field generated foamed cement slurries

D. Glosser [a,b], B. Kutchko [a,*], G. Benge [d], D. Crandall [c], M.T. Ley [e]

[a] United State Department of Energy, National Energy Technology Laboratory, Pittsburgh, PA, United States
[b] Oak Ridge Institute for Science Education, Oak Ridge, TN, United States
[c] United States Department of Energy, National Energy Technology Laboratory, Morgantown, WV 26507, United States
[d] Benge Consulting, The Woodlands, TX, United States
[e] Oklahoma State University, School of Civil and Environmental Engineering, Stillwater, OK 74078, United States

ARTICLE INFO

Article history:
Received 4 January 2016
Received in revised form
8 March 2016
Accepted 20 March 2016
Available online 21 March 2016

Keywords:
Energy
Foamed cement
Wellbores
Engineering

ABSTRACT

Foamed cement is a critical component for wellbore stability. The mechanical performance of a foamed cement depends on its microstructure, which in turn depends on the preparation method and attendant operational variables. Determination of cement stability for field use is based on laboratory testing protocols governed by API Recommended Practice 10B-4 (*API RP 10B-4*, 2015). However, laboratory and field operational variables contrast considerably in terms of scale, as well as slurry mixing and foaming processes. Here, laboratory and field operational processes are characterized within a physics-based framework. It is shown that the "atomization energy" imparted by the high pressure injection of nitrogen gas into the field mixed foamed cement slurry is – by a significant margin – the highest energy process, and has a major impact on the void system in the cement slurry. There is no analog for this high energy exchange in current laboratory cement preparation and testing protocols. Quantifying the energy exchanges across the laboratory and field processes provides a basis for understanding relative impacts of these variables on cement structure, and can ultimately lead to the development of practices to improve cement testing and performance.

1. Introduction

Foamed cements offer many beneficial properties over conventional cements including: higher ductility (Benge et al., 1996; Bour and Rickard, 2000; Frisch et al., 1999), reduction of lost circulation (Bour and Rickard, 2000), improved mud displacement, and improved gas migration control (Bour and Rickard, 2000; Frisch et al., 1999; White et al., 2000). The mechanical performance of a foamed cement depends on its microstructure, which in turn depends on the preparation method and attendant operational variables (Kutchko et al., 2015). Operational variables influence cement microstructure through various physical processes which impart or convert energy in the slurry as it moves through the mixing and foaming process. Characterizing these processes within a physics-based framework can provide a basis for understanding relative impacts of these variables on cement structure, and ultimately lead to the development of practices to improve cement testing and performance.

Foamed cement stability is tested under laboratory conditions according to API Recommended Practice 10B-4 (API RP 10B-4, 2015). In particular, surfactant and stabilizer packages are chosen based on the application, and laboratory tests are used to determine the relative concentration of material added to the slurry based on the stability test results. However, laboratory conditions contrast considerably from field conditions in terms of both scale of operations as well as equipment and process. Although these factors are known to influence the mechanical performance of foamed cement, little work has been done to tie laboratory and field operational variables to the energy balance across the slurry preparation processes, and consequently, the influence of energetics to foamed cement properties.

Recent experimental studies have established measurable differences in porosity, permeability, and bubble size distributions between laboratory generated and field generated cements (Kutchko et al., 2015). Stable foamed cement has a consistent density along the length of the column with a homogenous distribution of bubbles throughout the same column, commonly known as bubble size distribution (BSD). BSD of well formed foamed cement has been shown to have a uniform distribution of

* Corresponding author.
E-mail address: Barbara.Kutchko@netl.doe.gov (B. Kutchko).

http://dx.doi.org/10.1016/j.petrol.2016.03.014
0920-4105/

spherical, discreet bubbles to ensure that gas will not break out of the slurry (Nelson and Bell, 2006; Griffeth et al., 2004). Unstable foamed cements may have nonspherical and/or interconnected voids which can result in poorly contained sections caused by channelling in the well and density inhomogeneity (Nelson and Bell, 2006; Rozieres and de, Ferrier, 1991). These foams develop lower compressive strength and higher permeability than stable foamed cement (Nelson and Bell, 2006). Understanding the dynamics between operational variables; physical and mechanical processes influencing cements; and controls on the bubble size distribution is critical to understanding the stability of the foam in the well. We hope this information will lead to the development of improved laboratory testing methods, and improved field monitoring, to establish slurry design performance and further improve wellbore integrity.

This paper re-evaluates the role of operational process driven energetics in the foamed cement preparation process. In particular, we reassess the theory of mixing energy. The theory of mixing energy was first proposed in the 1980s (Hibbert et al., 1995; Orban et al., 1986; Vidick, 1990). The theory states that slurries with the same mixing energy inputs are expected to have identical properties. This would mean that if lab based mixing energy inputs matched field based mixing energy inputs, then, given the same admixture recipes, slurry properties would be identical. However, these studies did not focus on foamed cement paste and there has been minimal contemporary investigation into the influence of operational variables on foamed cement properties. Furthermore, experimental observations of lab and field cements have shown measurable differences between slurries prepared with similar mixing energies. The few peer review studies which have investigated these phenomena have primarily examined experimental relationships between cumulative mixing energy imparted to a slurry during the mixing process; and also have estimated the influence of shear rate on slurry properties (Vidick et al., 1990, Padgett et al., 1996). In these investigations, shear rate is treated as a separate phenomenon from mixing energy. These studies arrived at conflicting results with regard to the influence of cumulative mixing energy and shear rate on slurry properties. For example, some studies found no relationship between mixing energy and compressive strength (Padgett et al., 1996), while others relate compressive strength of cement directly to the mixing energy (Orban et al., 1986). The disagreement between these study results may be due to differences in experimental protocols, including differences in mixing equipment (e.g. coiled tubing versus no tubing; or different slurry volume or admixture recipes), or differences in sampling techniques, which in turn may influence slurry properties. In addition, these studies evaluate shear rate as being in contrast to energy, and not as a related quantity. Given the tight physical coupling between energy and shear rate, it is more appropriate to analyze them as dual quantities which can be altered by changes in operational processes.

Recent technological improvements that have been introduced in the field process necessitate reevaluation of the mixing energy calculations. For example, the shift from batch mixing to continuous mixing processes in the field have considerably altered both mixing apparatus geometry; and the total amount of mixing time a slurry spends in process prior to wellbore emplacement. But, perhaps the most notable operational variable in the field process which has henceforth been unquantified is the atomization energy imparted in the field foamed cement generator. During this process, nitrogen gas is injected at sonic velocity into the mixed slurry (McElfrish and Boncan, 1982). Furthermore, a qualitative accounting of the translation of the energy imparted from these processes to work; heat; and slurry kinetics is needed to better understand the energy balance in the foamed cement preparation process.

We build on prior studies by presenting a physics-based accounting for the mechanisms by which useable energy from mixing – and in the case of the field slurries – atomization, is imparted and transferred across the operational processes. Broadly speaking, the energy provided by the physical mixing, foaming, and atomization of slurry is the major input of useable energy imparted to a slurry. This energy may be translated or used for work on the slurry by a variety of processes, which are highly dependent on operational factors such as mixing time; slurry volume; and pumping pressures. While mixing and atomization energy cannot fully explain the differences observed between lab and field cements – and between cements produced with contrasting field protocols, it is nevertheless established as a critical parameter in the development of slurry microstructure and ultimately cement performance. This paper does not attempt to provide a full accounting of all of the physiochemical factors which could influence slurry properties. Here, we provide a first order approximation of energetics in the API standard lab testing protocol, and a first order approximation of energetics in a representative modern field process. To simplify computations, slurry admixture design packages in the lab and field are identical. The development of a physically based mathematical model to characterize these energies can be used by operators as a data point in the development of laboratory and field processes and packages to produce better performing cements.

2. Laboratory operations overview

Laboratory preparation of foamed cements occurs in two stages. The first stage is the mixing stage, and the second is the foaming stage. The American Petroleum Institute (API) recommended practices are the governing standards for laboratory preparation and testing for oilfield cements.

2.1. Base slurry

In the first laboratory mixing phase, the base slurry containing all additives except for foaming surfactants is mixed in a Waring blender (Fig. 1A and B). The Waring blender has approximately an 1100 mL volume capacity (and a standard mixing volume of 600 mL). Dry cement is added to water and additives within the blender. The RPM of the blender is controlled so the slurry is mixed at 4000 RPM for 15 s. Following this initial wetting of the cement, the Waring blender is then operated at 12,000 RPM for an additional 35 s.

2.2. Foamed slurry

Once the base slurry is mixed, the cement is then transferred to a second "foaming" blender, with a blender bowl capacity of approximately 1100 mL that has a sealed top and a stacked blade assembly. The mixing blades in the foaming blender are the same as used to mix the slurry, except rather than having a single blade at the bottom of the blender bowl, there are 5 sets of stacked blades (Fig. 1C). The proportion of slurry and foaming surfactant placed in the blender bowl will depend on the desired foam quality (gas content). For example, if the foam quality is 25%, then the amount of slurry and surfactant will occupy 75% of the volume. The foaming surfactant is added to the slurry after the base cement slurry, the top put on the blender and the contents are mixed for 15 s at 12,000 RPM. Although the time and RPM to foam the system is intended to be consistent, the actual operational time and rotational speed of the blender will vary based on how much cement is in the blender. While the API protocols recommend the RPM to be as close to 12,000 as possible, slurry volume build up and viscosity changes during foaming may not allow the blender